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EVALUATION OF METHODS TO DETERMINE THE IMPACT OF RESIDENTIAL WOOD BURNING ON AMBIENT AIR QUALITY

R. A. C. PROJECT NO. 426C

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R. A. C. PROJECT NO. 426C

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1 INTRODUCTION

During the fossil fuel shortage of the mid seventies, the availability of fuel wood prompted a significant increase in the use of residential wood stoves and fireplaces in many North American and Scandinavian communities. In Ontario, an increasing number of residents have been using wood stoves to substitute or augment heating provided by other means, as well as using wood burning fireplaces.

The increased use of residential wood as a fuel has resulted in deterioration of ambient and indoor air quality is several areas. The most direct evidence of this deterioration has been the increase in ambient total suspended particulate and carbon monoxide levels especially in areas that have poor atmospheric dispersion conditions. The concern over the air quality impact of residential wood combustion (RWC) is heightened by the composition of the emissions which have proven to contain toxic and carcinogenic species of which the polynuclear aromatic (PNA) compounds are most important. The PNA compounds emitted may undergo atmospheric chemical reactions with nitrogen oxides and ozone to produce a further variety of compounds which are potentially toxic or mutagenic.

Investigation of areas of non-attainment of carbon monoxide (CO) and aerosols revealed the significant impact of the collective effect of residential wood combustion (RWC). Special studies to determine the air quality impacts of RWC were undertaken in several wood-burning states especially in the Pacific Northwest - Colorado, Washington, Oregon, Idaho, as well as in states such as Minnesota, Michigan, New York, Maine, North Carolina, New Hampshire and Vermont. As can be anticipated, results of these studies confirmed the necessity to adopt standards of stove efficiency.

To complement these efforts, the emissions produced by woodstoves were investigated. Areas examined included: chemical composition, emission rates, and physical factors affecting the combustion process (moisture content, stove efficiency, etc.).

In Ontario, complaints regarding RWC emissions have been registered with municipal and regional government offices. The Ontario Ministry of the Environment has recognised the significance of the RWC sources in several communities and this study investigates the potential impact of RWC sources on ambient air quality.

This study has reviewed and compiled current information regarding the environmental impact of residential wood combustion. In the future, areas of significant potential for adverse air quality impacts from RWC in Ontario should be studied in order to characterize the extent of the impacts and to determine the need for appropriate control and abatement policies and strategies.

1.1 SCOPE AND OBJECTIVES

The objectives of this initial effort were to search the relevant literature, review articles and reports, and to summarise the current status on the following topics:

- current emission regulations and abatement strategies;
- source characterization;
- sampling techniques;
- analytical techniques;
- airshed impact studies;
- atmospheric (chemical and phase stability); and
- data analysis and assessment methods (tracer methods, chemical mass balance, receptor modelling, multivariate methods, etc.).

1.2 METHODOLOGY

The relevant literature databases were searched and the pertinent articles and reports were obtained. The information was categorized into the areas of interest and was reviewed in the context of the objectives. Invariably, some documents impinged upon several topics, and articles of this nature were reviewed successively. The approach of the literature review was to provide a concise, focused evaluation of current technology, rather than an article by article review.

The focus of this study was to gather relevant information and evaluate the technical merits of the past research efforts and to assess the potential for RWC impacts in Ontario and to recommend further action. The recommendations were based on an experimental design that will incorporate the most effective sampling and analytical methods to collect the optimum amount of information required to assess the RWC impacts and, where necessary resolve contributions from similar sources. The objective of a subsequent investigation will be to quantify and document the effects of RWC in selected areas in Ontario.

1.3 REPORT STRUCTURE

The remainder of this section provides a brief overview of combustion theory in order to elucidate the fundamental processes that occur in the combustion of wood. In subsequent sections, the various aspects of the study are presented in the following order:

i) legislation;
ii) sampling methodology;
iii) methods of analysis;
iv) other studies;
v) analysis of results; and
vi) recommendations.

1.4 OVERVIEW OF WOOD COMBUSTION PROCESS

The combustion of wood is dependent on many factors. A simplified view of the combustion process is that the fuel is exposed to thermal radiation; the organic compounds in the solid matrix are volatilized and the gaseous mixture produced combusts either by pilot ignition or spontaneous combustion. The products of combustion are organic matter and char, i.e.:

$$\text{Wood} \rightarrow \text{Volatilized Matter} + \text{Char}$$

Wood is a complex mixture of organic matter comprised of cellulose, hemicellulose and lignin. The proportions of these organic sugars vary depending on the type of wood and growth environment. The volatilization temperatures necessary for oxidative degradation also varies, with typical values being:

Hemicellulose	200 to 260°C
Cellulose	240 to 350°C
Lignin	280 to 500°C

The products of reaction are commonly referred to as char, tar, water, fine particulate matter and gases (CO, CO_2 as well as a myriad of organic compounds). Chemically, the combustion process in its simplistic form is given by:

$$C + O_2 \rightarrow CO + CO_2$$
$$CO + O_2 \rightarrow CO_2^*$$
$$CO_2^* \rightarrow CO_2 + h\nu$$

where the released photon energy (hv) is the distinctive blue hue visible in wood fires. The "tar" fraction of reaction products is a composition of organic material of low volatility. (One of the compounds of "tar" is lavoglucosan. Lavoglucosan has been investigated as a possible tracer compound for wood smoke). In fact, many factors influence the gasification and combustion processes and the nature (composition) and amounts of emissions. These factors include both the chemical composition of the fuel wood, and the physical factors (e.g., stove type and burn conditions) affecting the combustion process. This brief overview illustrates the complexity of the combustion process and indicates some of the basis for the considerable efforts required to characterize emissions and to assess RWC air quality impacts.

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2 REGULATORY ASPECTS AND CONTROL STRATEGIES

Wood heating appliances are regulated by a wide variety of programs and provisions that either directly or indirectly impact upon the design, testing, performance and installation of the appliance with respect to air contaminant emissions. In several areas of the United States especially in the northwest, the increased use of residential wood heating appliances has forced many areas to develop and implement measures designed to regulate the amount of emissions produced by woodstoves. The measures fall into three categories:

1. the development of efficiency, design and emission codes and standards for wood burning appliances;
2. setting maximum permissible air pollution levels and installation regulations; and
3. control strategies and programs and non-regulatory activities.

Regulations for the most part include:

- design and/or technology standards (woodstove certification requirements);
- emission standards for particulates, and in some cases carbon monoxide and/or opacity;
- voluntary and mandatory burning curtailment on days of poor air quality; and
- limitation of the number of installations.

Control strategies and programs vary and typically include one or more of the following elements:

- public education programs;
- voluntary burning curtailment;
- woodstove retrofits (with catalytic converters);
- certified woodstove replacements;
- firewood seasoning rules;
- weatherization of wood-heated homes;
- wood stove licensing; and
- incentive programs such as low interest or no interest loans, tax credits, preferred utility rates, rebates, etc. for replacement and or upgrading of units.

The regulatory and control strategies currently in place in Canada and the United States are described in this section.

2.1 CANADA

To date, there are no provincial or federal regulations that limit or control emissions from residential woodburning or heating appliances. Neighbour-to-neighbour complaints regarding residential wood combustion emissions have been received in many provinces, particularly in areas prone to poor dispersion of woodstove emissions. However, the introduction of controls has not occurred.

The Ontario Ministry of the Environment Regional and District Offices were contacted to obtain complaint data regarding residential wood combustion emission. A request for complaint data from the past three heating seasons of both total and RWC complaints was made, however, some districts could not provide the information due to time constraints and staff limitations. Table 2.1 summarizes the data obtained.

TABLE 2.1

Summary of Residential Wood Complaint Data (1986-1989) for Selected Areas in Ontario

District	Total RWC Complaints			Total Complaints		
	1986/87	1987/88	1988/89	1986/87	1987/88	1988/89
Northeast Region	12	29	7	155	227	56
Sault Ste. Marie		3	0			
North Bay		12	2			
Sudbury		1	1			
Timmins		13	4			
Thunder Bay	10	10[a]	10[b]			
Kenora	5	5[a]	5[b]			
Hamilton/Wentworth/ Norfolk	6	13	9	115	170	177
Cornwall	4	8	0	57	337	59
Ottawa	9	3	1	17	11	6
Kingston	8	0	0	151	47	51
Gravenhurst	6 to 8 over 2 seasons					
Barrie	10 over 2 seasons					
Oakville	75 over 3 seasons					
Peterborough	36 over 3 seasons					
Windsor/Sarnia/London	34 over 2 seasons					

NA = Not available

[a] all RWC are now handled by the muncipality

[b] a surge of RWC complaints ~ 6-7 years ago when wood burning increased in popularity - complaints have decreased since.

Although the data in Table 2.1 are limited, it is evident that, by far, the largest number of complaints occurred in 1987/88.

A review of meteorological data (Climatic Perspectives) indicated that an early snowfall in the beginning of December 1987 was followed by record high and low temperature fluctuations. This may explain the large number of complaints received during the 1987-1988 heating season as a number of "cold starts" would have occurred.

Canadian Standards Association

In early 1984, the Canadian Standards Association assembled a Committee to develop a comprehensive performance test standard for wood stoves. The Canadian Wood Energy Institute and the Department of Energy, Mines and Resources (EMR) triggered the formation of the Committee. Its mandate was two-fold. Firstly, to develop test procedures designed to provide reproducible performance measures. Secondly, to assess whether performance testing should be voluntary or mandatory, and whether pass/fail criteria should be established. A labelling format also had to be agreed upon.

The preliminary standard was developed and incorporated specific guidelines regarding test facilities, instrumentation, fuelling methods, testing procedures and, finally, the manner in which test results would be calculated for such key indicators as heat output, average stack temperature, burn time (duration of burn), appliance efficiency and emissions (Braaten, 1984). The preliminary standard however did not incoproate maximum emission nor minimum efficiency standards and was never promulgated. The Committee is currently revising the standard to incorpoate both maximum emissions and minimum efficiency standards similar to EPA federal standards. The revised standard is not yet available in draft form. A draft form should be ready during the next Committee meeting in February 1990 (B. Wier, 1989). Some effort has been made by the Committee to harmoized development of the CSA standard with EPA.

CWEI Training and Certification Program

The Canadian Wood Energy Institute (CWEI), a non-profit organization, has developed a training and certification program (Wood Energy technical Training (WETT)) geared to woodburning appliance distributors, installers, contractors, inspectors (Building, Fire and Insurance) and chimney sweeps. EMR has alsois funding the development of a manual, covering all facets of proper woodburning appliance installation, operation and maintenance as part of this program. Among other objectives, it is hoped that the program will improve woodburning practices, stove efficiency and installation procedures. Improved operation can be expected to help reduce emissions.

Appliance Performance Testing

EMR is sponsoring a Performance Test Program aimed at encouraging Canadian wood stove manufacturers to test their appliances against both CSA and U.S. Environmental Protection Agency standards. The objective of this Program is to encourage adoption by Canadian industry of the recently promulgated CSA standard, while at the same time ensuring that Canadian-made appliances will be exportable to the U.S.

2.2 UNITED STATES

2.2.1 Federal Regulations

On February 18, 1987, the Environmental Protection Agency (EPA) proposed performance standards and rules for new residential wood heaters. The rules state that wood heaters manufactured on or after July 1, 1988 or retailed on or after July 1, 1990 must be certified (CFR, 1988). That is, prototype wood heaters representing a model line must demonstrate specific emission control capabilities over a range of operating conditions. Only accredited testing laboratories that have demonstrated administrative and technical capabilities may perform the certification emission testing of wood heaters. The federal regulation is modelled after the State of Oregon 1988 particulate matter emissions standards and certification program (Wesland, 1989). All woodstoves are subject to this law, with the exception of open masonry fireplaces constructed on site, boilers, furnaces and cookstoves.

A summary of the specifics relating to the federal regulation 40 CFR Part 60.530 Sub Part AAA - Standards of Performance for New Residential Wood Heaters is provided below:

Manufactured on or after	Sold Retail on or after	Equipped With Catalytic Combustion	Particulate Matter Emission Limit (weighted average)
July 1, 1988	July 1, 1990	Yes	5.5 g/h
July 1, 1988	July 1, 1990	No	8.5 g/h
July 1, 1990	July 1, 1992	Yes	4.1 g/h
July 1, 1990	July 1, 1992	No	7.5 g/h

Appendix A of the code describes the test methods and procedures to be used to determine compliance with the standards and requirements for certification. The principal methods are:

Method 28 - Certification and auditing of Wood Heaters (used to establish the certification test conditions and the particulate matter weighed emission results).

Method 5G - Determination of Particulate Emissions From Wood Heaters From A Dilution Tunnel Sampling Location

Method 5H - Determination of Particulate Emissions From Wood Heaters From A Stack Location

Method 28A - Measurement of Air to Fuel Ratio and Minimum Achievable Burn Rates for Wood-Fired Appliances

A schematic diagram of the 5G and 5H methods are provided in Appendix B. As previously noted, the certification testing must be performed by testing laboratories accredited by EPA for this purpose. The EPA accreditation requires the laboratory to complete a number of administrative items and to complete a demonstration of proficiency using the emission procedures defined in the regulation. The Emission Measurement Branch (EMB) is responsible for the laboratory accreditation program.

2.2.2 State and Municipal Regulations

Many states have developed and implemented their own legislation regarding wood heater emission limits and performance standards. Information obtained regarding state/municipal regulations and abatement programs is summarized below. A summary of residential wood combustion control regulations in the U.S. is given in Table 2.2.

A. OREGON

Oregon adopted a mandatory woodstove certification program in June 1984 (Kowalczyk, 1985), which had five major elements:

1. a testing procedure for stove emissions and efficiency;
2. particulate emission standards;
3. an accreditation process for laboratory testing;
4. stove labelling requirements; and
5. certification procedures;

Woodstove and fireplace insert emission standards went into effect July 1, 1986. More stringent standards came into effect on July 1, 1988 (Omni, 1986). The certification emission standards are as follows:

TABLE 2.2

Residential Wood Combustion Control Regulations In the United States

Area	Regulation/Ordinance Effective Date	Control Stragegy			
		Burning Curtailment	Design/Technology Standards	Emission Limits	Other
Juneau (Mendenhall Valley, Lemon Creek Valley) Alaska	Alaska Air Quality Control Regulations 18AAC 50 (10/30/83) Juneau Ordinance 84-30 (5/21/84) 88-59 (5/12/88) Memorandum of Agreement - Alaska DEC and Borough of Juneau for Air Pollution Control	Voluntary and mandatory phases. Mandatory prohibition occurs when an air emergency is declared by the City and Borough of Juneau.	Designates clean-burning woodstoves for Class I Permit issuance which allows operation during an air pollution alert. Class I Permit issued for EPA Certified woodstoves.	50% capacity for no more than 15 minutes in any hour. Alert status initiated when ambient TSP meets or exceeds 150 μg/m³ (100 μg/m³ effective 11/1/86). Sale of new woodstoves limited to certified units as of 8/1/86 (adopts EPA Certification).	Public education program emphasizes shift in firewood gathering from fall to spring. No new woodstoves may be sold within City and Borough of Juneau after 8/1/86 unless weighted emissions are less than 6 g/hr after 7/1/88, less than 4 g/hr.
Lake Tahoe (Regional Planning Agency Area) California and Nevada	Tahoe Regional Planning Agency - Air Quality Regulatory Plan (currently interim standard).		Only "New Technology" woodstoves allowed to be installed in major new developments. Fireplaces must have: a) outside air combustion source; b) glass doors; and c) fan assisted heat exchangers.		
Placer Co. (Lake Tahoe area) California	Land Use Permits				Conditional use permit required to install new wood-burning devices in major new developments.
Colorado (statewide)	Colorado Department of Health, Air Pollution Control Division: Regulation #4 (7/30/85)		Fireplace design standards to be adopted by 7/1/87.	Statewide Certification Program. Provisions for two separate testing methods (one identical to Oregon Method). Sets limits for each testing method based on appliance heat output (min/max).	Reciprocal Certification agreement with the State of Oregon, accepting both Oregon Method 7 and ASTM-Oregon Hybrid. Public education program.

TABLE 2.2 (Cont'd)

Residential Wood Combustion Control Regulations in the United States

		Control Stragegy			
Area	Regulation/Ordinance Effective Date	Burning Curtailment	Design/Technology Standards	Emission Limits	Other
Aspen Colorado	Aspen Municipal Code, Supplement No. 23 (9/83) Aspen Municipal Ordinance No. 12 - Series of 1983 (4/25/83)	(See "Pitkin County".)	For fireplace glass doors and outside combustion air. Certified stoves must meet Oregon test procedure.	Refer to Colorado.	Offset policy for installing additional conventional wood-burning devices. Sets limits on number of wood-burning devices for new installation. Exceptions for "clean-burning" devices.
Vail Colorado	Vail Ordinance No. 24 Series of 1983 Ch. 8.28 (7/19/83)		Devices to improve fireplace efficiency (e g. excess air) are required.	Refer to Colorado.	Sets limits on new installations, enforced through issuance of building permit.
Pitkin County Colorado	Air Pollution Requirements of the Pitkin County Code, Title III, Article 4. Pitkin Co. Resolution No. 83-7 (1/24/83). Pitkin Co. Resolution No. 77-104 (8/22/77). Pitkin Co. Resolution No. 85-14 (2/11/85).	Burning restrictions may be imposed by the County Air Advisory Board, based upon ambient atmosphreic concentrations of CO, hydrocarbons and particulates.	Fireplaces must be equipped with devices to improve efficiency.	Refer to Colorado.	Set limits on new installations. Provides for pollution offset variance for unit replacement with "clean burner".
San Miguel County - Telluride; Beavercreek, Snowmass Village Colorado	Beavercreek Recreation Area Cooperative Agreement of 9/15/81 (10/15/81) San Miguel Co. Resolution No. 1985-12 (5/31/85) Telluride Ordinance No. 646 (2/25/84) Telluride Resolution No. 1985-12 (6/17/85) Telluride Mountain Village PUD Fireplace Construction Regulations (7/11/86) Snowmass Village Ordinance No 3 Series of 1980 (3/3/80)	Mandatory prohibition of fireplace use during pollution episodes at Beavercreek. Episodes declared by the Resort Co., when ambient standard may be exceeded.	For fireplaces in Beavercreek.	Refer to Colorado.	In Crested Butte, stringent insulation requirements. In Beavercreek, woodstoves prohibited. In Telluride, six month moratorium on the installation of new woodstoves and fireplaces (2/85 to 7/85).

TABLE 2.2 (Cont'd)

Residential Wood Combustion Control Regulations In the United States

		Control Stragegy			
Area	Regulation/Ordinance Effective Date	Burning Curtailment	Design/Technology Standards	Emission Limits	Other
Albuquerque New Mexico		Voluntary - announced by red light atop downtown building when CO levels are high.			
Montana (statewide)	Senate Bill 309 (1/1/85) Montana Code - Subchapter 17			Accepts Oregon and Colorado certification for woodstoves.	Tax credits for purchase of certified stoves. Retroactive to 1/1/85.
Missoule Montana	Missoula City-County Air Quality Control Regulations: Section X, 4100 Section SII (11/20/84).	Provides for burning curtailment with exceptions for certified woodstoves.	Class I permits issued for Oregon Certified stove.	During an Air Pollution Alert, no visible emissions from solid fuel burning devices unless a Class I or other special permit issued. 10% opacity limit in effect for Class I permit holders during an Air Pollution Alert.	Public Education Program.
Helena Montana	Lewis and Clark Co. Clean Air Ordinance (10/15/85)	Provides for burning curtailment during designated "pool" air quality alert stages. Prohibits burning of high sulfur coal.			Provides for civil penalties based on non-compliance.
Washoe County (Reno) Nevada	Washoe Co. District Board of Health - Air Pollution Control Regulations (5/26/84).	Voluntary and mandatory phases. Mandatory prohibition occurs when TSP levels read 625 $\mu g/m^3$ or CO levels reach 30 ppm.	Restricts sale, advertising and installation of woodstoves to those certified by Oregon and Colorado, as of November 1987.	PSI 150	Public Education Program provides "Wood Burners Guide" and guide for developers to reduce need for residential wood burning.
Great Neck Plaza New York	Village of Great Neck Plaza; Local Law No. 14 of 1984 (3/6/85).				Prohibits fireplace operation in designated areas within village.
Yakima County Washington	First Amendment to the Consolidated Regulations of the County Clean Air Authority (8/6/86).	Restricts the Woodsmoke Opacity Limitation to 20% during a designated Air Pollution Episode.	Adopts the Oregon Woodstove Certification Standards for all woodstoves offered for retail sale after 12/31/86.	Woodsmoke Opacity Limitations: 40% during "normal" operations; 20% during Air Pollution Episode. Adopts particulate emission standards as specified in Oregon Woodstove Certification Standards	Public Education Program for both ordinance violators and the general public.

TABLE 2.2 (Cont'd)

Residential Wood Combustion Control Regulations In the United States

Area	Regulation/Ordinance Effective Date	Control Stragegy			
		Burning Curtailment	Design/Technology Standards	Emission Limits	Other
Oregon (statewide)	Oregon Administrative Rules; Chapter 340, Division 21 - Department of Environmental Quality Woodstove Certification (11/84).		Sales limited to those woodstoves that pass Oregon Certification Tests.	Statewide Certification Program. Woodstoves sold after 7/1/86: Partic. Limit (g/hr) Non-Cat. — Catalyst 1986 - 15 — 1986 - 6 1988 - 9 — 1988 - 4	State DEQ conducts public education programs to encourage "clean burning" practices, e g proper wood drying technique, proper sizing of stoves, etc.
Medford Oregon Jackson County	Medford/Ashland AQMA, State Implementation Plan: Section 4.10: Jackson Co. Ordinance No. 84-29 (10/17/84) City of Medford Ordinance No. 4740 (2/17/84) Certain mandatory provisions of both ordinance have been relaxed in favour of voluntary cooperation by the public.	Voluntary burning curtailment as per advisory issued through media by City of Medford: Condition — Burning Green — OK Yellow — Use Discretion Red — Do Not Burn		Refer to Oregon.	Public Education Program encourage spring cutting of firewood. Weatherization requirements for woodstove installations - administered by issuance of building permit.
Northampton Massachusetts	Northampton Board of Health - Regulations Governing Emissions from Solid Fuel Burning Devices (4/2/85).			40% Opacity Limit	Public Education Program.
Lakewood Colorado	City of Lakewood Ordinance	Mandatory curtailment to meet CO air quality standard.		Air pollution index of 150 or above. Measure of CO_2 and O_3.	Public Education Program.

TABLE 2.2 (Cont'd)

Residential Wood Combustion Control Regulations in the United States

Area	Regulation/Ordinance Effective Date	Control Stragegy			
		Burning Curtailment	Design/Technology Standards	Emission Limits	Other
Boisie Idaho	City Ordinance	Voluntary curtailment 1984-1986. Mandatory 1988. PM10 of 110 μg/m³ and air stagnation.	Prohibits Installation of DEQ Certified Appliances (Oregon).	Refer to Oregon.	Economic incentive programs to encourage replacement of non-certified appliances. Home insurance and some types of mortgages/loans cannot be obtained unless stoves are inspected for proper installation.
U.S.A.	Code of Federal Regulations 40 CFR 60.530 Appendix A		Federal Woodstove Certification Programs.	Woodstoves sold July 1, 1990. Non-Cat Catalyst 8.5 g/h 5.5 g/h After July 1, 1990: Non-Cat Catalyst 7.5 g/h 4.1 g/h	

	Particulate Emission Rates	
	Catalytic Stoves	Non-Catalytic Stoves
Prior to July 1, 1988	6 g/h	15 g/h
After July 1, 1988	4 g/h	9 g/h

Manufacturers must have each stove model tested by a laboratory approved by the Department of Environmental Quality (DEQ). The laboratory measures emissions and efficiency when the stove is operating at low, medium, high and maximum heat output.

In May of 1989, a Senate Bill (422) (State of Oregon, 1989), was introduced to control pollution from woodstoves in five areas of the state which do not meet current air quality standards. The areas include Eugene-Springfield, Grant Pass, Klamath Falls, La Grande and Medford. The essential features of the Bill are summarized as follows:

1. Requires DEQ to establish a state-wide residential wood-heating opacity limit and emission reduction level.
2. Prohibits selling of unseasoned firewood during certain months and burning certain products (e.g., vegetative debris or household waste).
3. Provides incentives, available until July 1, 1993, to convert to more efficient forms of heating.
4. Prohibits installation of woodstoves unless the wood is certified by DEQ and the building code inspector.

This bill was proposed but apparently not passed. (Core, 1989). Other potential amendments to Senate Bill-422 are summarized below:

1. Restrict Annual Woodstove Household Fee to Areas Exceeding PM-10 Standards. Presently these areas would be Eugene-Springfield, Grants Pass, Klamath Falls, La Grande, and Medford.

2. Extend Annual Fee to All Wood Burning Devices. This would encompass fireplaces which also contribute to PM-10 non-attainment. Public education and curtailment programs must be directed to all wood burning devices including fireplaces. Additional revenue generated from fireplace households will provide a funded financial incentive program to encourage conversions to lower polluting systems.

3. Reduce the Annual Woodburning Household fee from \$20/y to \$10/y for owners of Certified Stoves. Certified stoves reduce woodsmoke emissions in home use by about 50%. Public education and surveillance programs are needed for certified stoves as well to insure they maintain this emission reduction.

4. Change Fee Collection Mechanism From Income Tax System to Permits Sold By Agents of DEQ. While permits are a costlier way of collecting this fee, the state income tax system is not considered by the Revenue Department as an appropriate collection system for any type of fee especially for fees that would not be assessed state wide.

5. Reduce Maximum Tax Credit from \$500 to \$300. This will reduce the impact on the revenue (General Fund) from \$2,240,000/y to \$1,344,000/y. Tax credits would be graduated and proportional to the emission reduction potential of the system with \$300 available for replacements with non-wood burning systems, \$270 for pellet systems, \$195 for durable certified stoves, and \$135 for other certified stoves.

Use of User Fee Revenue - (Approx. \$1,705,000/yr)

1. Provides low interest loans to approximately 25-40% of the anticipated wood heating system upgrades.

2. Provides $300 rebate to the expected 5% of the woodheating system upgrades that select non-wood burning systems.

3. Provide approximately $180,000/y needed by local governments in PM-10 non-attainment areas to provide public education, and operate curtailment and opacity programs.

4. Provides DEQ with approximately $330,000/y needed to administer tax credits, loan and rebate programs and enforce unseasoned wood programs and coordinate public education. Administration costs are based to a great extent on the costs to the Department of Energy to run similar tax credit, low interest loan and rebate programs for energy conservation measures.

Jackson County (Baston, 1987) (including the cities of Medford and Central Point) have designed and implemented ordinances which include:

1. Public education in the areas of proper woodstove operation and regarding firewood moisture control - encouraging spring firewood cutting at nearby national forests and through incentives to individuals and commercial cutters.

2. Mandatory weatherization - for homes wishing to install woodstoves. Financial incentives including low interest loans, tax credits and help from utilities was provided.

3. Voluntary curtailment during air stagnation advisories unless there is no alternative heat source.

4. Proper sizing of new woodstoves to household heating requirements to be evaluated during stove permit process.

5. All new homes with woodstoves must have an alternative heat source.

Portland and **Eugene**, Oregon have introduced a variety of weatherization programs. The Cities and local utilities offer no-interest or low-interest loans, free home energy audits and help in doing the work or in locating a contractor to do it.

Klamath County, Oregon, also has implemented a voluntary wood burning advisory program. **Green** means "it is okay to burn", **yellow** "reduce wood burning" and **red** "do not burn". The county is also actively pursuing financial incentives or subsidies for conversion to more efficient units (Klamath CPC, 1988).

B. COLORADO

The state of Colorado has a state-wide regulation on the sale of new woodstoves which came into effect on June 30, 1988 (Colorado AQCC, 1988). Only stoves which are certified as meeting emission standards may be advertised or sold in Colorado. This regulation includes a particulate emission standard as well as limitations for carbon monoxide emissions (Table 2.3). Unique to Colorado's woodstove certification requirements is the choice of two emission testing methods. One is identical to the Oregon woodstove certification method. The other is a hybrid of the Oregon method and the American Society of Testing and Materials (ASTM) procedures (i.e., use of dilution tunnel for emission testing) for determining carbon monoxide and particulate emissions. There are two phases to this regulation; the Phase I standard was in effect up to June 30, 1988, after that date Phase II standards apply. The state is currently considering a Phase III of the regulation which will be more stringent in terms of emission standards. (Cassin, 1989).

Control strategies for residential wood combustion have been adopted in several Colorado ski communities including Telluride (San Miguel County), Aspen (Pitkin County), Beavercreek, Vail, Snowmass Village, Crested Butte, Silverthorn and Steamboat Springs (Burton, 1984). While specific measures in these communities may vary, most have adopted limits on the installation of new certified wood heating devices, design standards, performance

TABLE 2.3

State: Colorado - Regulation No. 4
- Regulation on the Sale of New Woodstoves
Effective - June 30, 1988[a]

			Emission Standards		
	Date	Heat Output BTU/h	Particulate Emission g/h	Carbon Monoxide g/h	Testing Method
Phase I	Prior to July 1, 1988	≤40,000	30	400	Oregon
		≤40,000	22	400	ASTM
		>40,000	≤37 and 1 g/h for each 1000 BTU/h heat output	≤800 and 10 g/h for each 1000 BTU/h heat output	Oregon
		>40,000	≤30 and 0.7 g/h for each 1000 BTU/h heat output	≤800 and 10 g/h for each 1000 BTU/h heat output	ASTM
Phase II	On or After July 1, 1988	≤40,000	12	200	Oregon
			8.5	200	ASTM
		>40,000	≤15 and 0.4 g/h for each 1000 BTU/h heat output	≤400 and 5 g/h for each 1000 BTU/h heat output	Oregon
		>40,000	≤12 and 0.3 g/h for each 1000 BTU/hr heat output	≤400 and 5 g/h for each 1000 BTU/hr heat output	ASTM

(a) Colorado Air Quality Control Commission, 1988 standards, voluntary or mandatory curtailment of woodburning during air pollution episodes and public education. Information regarding these control strategies are provided below.

Crested Butte (Denver Metropolitan AQC, 1987) requires that all wood stoves installed after May 1987 must meet Colorado Phase II certification standard. Old wood stoves and fireplaces must be replaced with certified units when ownership of real estate is transferred.

The city also levies a $20 per month excise tax on all solid fuel burning devices (i.e., woodstoves). There are however four exemptions to the excise tax:

1. Approved certified woodstoves;
2. Coal burning devices which are exclusive sources of heating,
3. Solid fuel devices which are retrofitted with an approved pollution control device; and
4. Low income households.

The city also limits woodstoves to one per new building, provided the building meets very stringent insulation standards. Owners of woodstoves and fireplaces (i.e., solid fuel burning devices) are encouraged to replace non-certified units with certified units by September 1, 1989. A replacement will result in exemption from the excise tax. Any one violating this Ordinance (Ordinance No. 7, Series 1986, Article 6-5) may be fined up to $300 for each offence. Each day that violation exists is considered a separate offence.

Steamboat Springs has an extensive woodstove (and fireplace/coal stove) replacement program (Gay, 1986). The Ordinance #977 (Chapter 8.48 - Air Pollution) requires that all solid fuel burning devices in the City of Steamboat Springs must be registered with the City by August 3, 1987. Failing to register could lead to a fine of up to $300 a day and/or a jail term of up to

90 days or serve up to 10 hours of community work. Only certified woodstoves may be installed and the ordinance limits the number of new installations to one per building. Non-approved devices must be converted to approved units as follows:

1. woodstoves - by February 3, 1989;
2 fireplaces - by February 3, 1990; and
3. coal stokers - 8 months after sale of property.

Fireplace must be replaced with a certified fireplace insert or converted to use gas logs.

Telluride has four City Ordinances for solid fuel burning devices (#677, 735, 756 and 764) (Denver Metropolitan AQC, 1987). All owners of properties must have obtained a permit for solid fuel burning devices by September 15, 1985. Permits were renewable on or before September 15, 1988 after an inspection by the city Building Department verifying compliance. Only one device may be operated per dwelling. Permits could be sold on the open market. After September 15, 1985 only one certified device could be installed per dwelling once a permit had been issued. No coal could be burned after September 15, 1985 unless it was the primary source of heat. No coal could be burned after September 15, 1988. A rebate program within the three year period of the program (Sept. 15, 1985 to Sept. 15, 1988) was set up as follows:

Replacing an old device with a certified one:

1985 - 1986	$200.00 rebate
1986 - 1987	$150.00 rebate
1987 - 1988	$100.00 rebate

For a total conversion to electric or gas heat the rebate was set as:

1986 - 1987	$750.00
1987 - 1988	$250.00

Denver Metropolitan Local Governments (Denver Metropolitan AQC, 1987), consisting of five of the largest metropolitan area cities (Arvada, Aurora, Boulder, Denver and Lakewood/Westminister) have adopted mandatory bans on woodburning during high pollution days. High pollution "alerts" are called when carbon monoxide levels are projected to exceed 12 parts per million (ppm). Unlike other cities, alerts are not called in the metropolitan Denver region when particulate standards are projected to be violated.

Enforcement of the episodic no-burn restrictions is governed by provisions in the municipal ordinances. All municipalities (with the exception of Denver) use existing municipal personnel to enforce their no-burn ordinances. Denver hires temporary part-time personnel during the high pollution season. Penalties also vary. All five cities give warnings for the first violation. Fines for a second offence range from written warning to a $300 fine. Fine for third offenses range from a summons to appear before a judge to a fine of up to $999 and a possible jail term.

Exemption to the no-burn ban include:

1. sole source of heat; and
2. certified Colorado Phase II stoves.

Pitkin County (Aspen) (Burton, 1984; City of Aspen, 1988) adopted ordinances limiting the number of new fireplaces and requiring design standards such as 1) glass doors; 2) outside combustion air; and 3) fan-assisted heat exchangers. These standards were also adopted by Vail and the Lake Tahoe area. Colorado Springs and Aspen are considering implementing an ordinance similar to Telluride requiring all non-certified woodstoves to be replaced or providing incentive programs for owners to upgrade. (Cassin, 1989).

Both **Vail** and **Snowmass Village** (Burton, 1984) have passed ordinances allowing only one certified unit per dwelling.

C. MONTANA

The state of Montana has developed and implemented a program designed to provide an incentive for the consumer to buy and install only clean burning, low emission wood burning devices. The incentive is based on a tax credit to be applied against the consumer's state income tax liability. Specifically, the incentive applies to the purchase and installation of certified woodstoves between January 1, 1985 and December 31, 1992. The tax claim is equal to 10 percent of the first $1000 and 5 percent of the next $3000 of the system cost for woodstoves emitting no more than 6 g/h of particulate emissions.

The **County of Missoula** (Denver Metropolitan AQC, 1987; Baston, 1987) has one of the nation's most stringent woodstove emissions programs. The Missoula City/County Health Department has implemented air quality control regulations which address residential wood heating appliances and provide for emergency procedures during periods of air stagnation. Specifically the control measures include a visible emissions limitation of 40 percent opacity, requires woodstove certification (6 g/h particulate emission limitation) for new installations, establishes a permit requirement system, provides for curtailment of wood burning during air pollution episodes and provides for enforcement of non-compliance. Missoula does accept woodstoves certified by the state of Oregon.

Helena, Montana (Denver Metropolitan AQC, 1987) (Lewis and Clark County) issued a clean air ordinance during October 1985. The ordinance establishes air quality alert stages (good, watch, and poor) and provides for public notification when poor air quality conditions are expected. The ordinance prohibits the operation of residential solid fuel burning devices on designated "poor" air quality days. The County Health Department operates high volume and PM-10 samplers within the Lewis and Clark County Air Pollution Control District to determine air quality levels. The county ordinance provides for "hardship" exemptions and also provides for warnings and civil penalties in the event of non-compliance.

D. WASHINGTON

The state of Washington has a state woodsmoke control law which has he following five major provisions (Comis, 1988):

1. A state-wide education program, funded through a special fee from new woodstove sales.

2. Emission standards for new woodstoves, effective July 1, 1988 (same as Federal emission standard). Only certified new stoves may be sold.

3. Starting January 15, 1988, the opacity of smoke emitted from a woodstove or fireplace is not to exceed 40%. Beginning July 1, 1990, the opacity of such smoke is not to exceed 20%. There is an exception from these opacity limits during the starting of a new fire for 20 minutes in any four hour period.

4. The following materials are not allowed to be burned in a woodstove or fireplace:

    - garbage;
    - plastic products;
    - animals;
    - paint;
    - treated wood;
    - rubber products;
    - asphaltic materials; and
    - waste petroleum products.

    This provision of the law is to encourage the use of properly seasoned firewood.

5. During an air pollution episode, there is mandatory curtailment of the use of woodstoves, fireplaces, coal stoves and cook stoves (in both residences and commercial establishments). The State Department of Ecology or the local air pollution authority is responsible for determining poor air quality conditions and declaring no burn periods.

Residences which rely solely on wood heat are permitted to continue to use stoves and fireplaces during episodes and periods with impaired air quality.

Yakima County (Washington) (Batson, 1987) has a mandatory wood burning curtailment program in effect during exceedences of specified ambient TSP levels (150 $\mu g/m^3$). The elements of the County regulation are similar to the DEQ requirements. All new woodstoves offered for sale within the Yakima County after December 31, 1986 must be certified.

In June of 1986, the **Okanojan County** (Comis, 1988) of Washington proposed a draft woodsmoke ordinance requiring the installation of certified stoves and a woodburning curtailment program.

E. ALASKA

The State of Alaska has a state wide regulation limiting the opacity of residential wood combustion emissions to 50 percent, the regulation are enacted only in the Mendenhall Valley and Lemon Creek Valley areas of Juneau, Alaska (Gilbertson, 1988).

As of January 16, 1986, all new woodstoves either sold or installed in Juneau, had to be certified as emitting less than 6 grams of particulate matter per hour (as measured under the State of Oregon Testing Procedures) (City of Juneau, Alaska, 1985). On December 5, 1988 the City and Borough of Juneau adopted the US Code 40 CFR, Part 60, Subpart AAA. Emission criteria are as follows:

	With Catalytic Devices	Without Catalytic Devices
	Particulate Emission Rates	
Dec. 1988	6 g/h	8.5 g/h
July 1, 1990	4.1 g/h	7.5 g/h

Permits are issued for new woodstoves to be operated during an air pollution alert and are valid for a period of two years. An air pollution alert is in effect when the ambient concentration of particulate matter 10 micrometers and less in diameter (PM-10) equals or exceeds 92 $\mu g/m^3$. Permits are eligible for renewal as long as the woodstove continues to meet the emission standard in effect at the time the permit was originally issued.

After January 19, 1989 no new woodstove may be sold in Juneau unless it is certified to meet the above standard. The public was given an incentive to use the certified wood stoves through the adoption of a two stage air episode plan. During the first stage (called an "air alert"), only certified wood stoves could be used; the second stage ("air emergency") required all wood stove users (including certified stoves) to halt burning.

The City and Borough of Juneau Building Code was amended to require minimum insulation standards of R-30 ceilings and R-19 wall and floors. (Previously there were no requirements for home insulations) (Gilbertson, 1988). Regulations were adopted which disallowed wood stoves as a sole source of heat and required a back-up system capable of heating the living area of a house to 70°F. The State of Alaska has a program to provide low interest loans to persons who purchase catalytic wood stoves and an energy assistance program to low-income persons providing grants for energy costs based on income.

F. Other Jurisdictions

In the **Reno, Nevada** area, the **Washoe** County (Batson, 1987) District Board of Health adopted regulations establishing episode criteria levels based on concentrations of CO, O_3 and suspended particulates. In September 1985, the Washoe County Air Quality Board passed an ordinance which restricts the sale or installation of woodstoves or fireplace inserts to only those which meet the following particulate emission criteria: 6 g/h for catalytic woodstoves and 15 g/h for non-catalytic. Enforcement provisions include inspection by the District Health Department of wholesale and retail woodstoves and the power to cling building permits where non-catalytic devices are to be used.

The City of **Boise, Idaho** (Batson, 1987) has implemented ordinances prohibiting the installation of non-certified devices as well as mandatory woodburning curtailment during air quality alerts. Incentive programs to encourage the replacement of older uncontrolled stoves with certified appliances have been introduced. These programs include:

- low-interest loans;
- in homes with wood or coal as a sole source of heat, a 15 year 6% loan is available if an electric or gas furnace is installed; and
- home insurance and some types of home mortgage loans cannot be obtained unless stoves are inspected for proper installation.

Exemption to the burning ban may be granted in one of the following situations:

- Woodheating appliance is certified.
- Woodheating appliance is sole source of heat.
- Using an alternative heating source would cause an unreasonable economic hardship.

The town of **Northhampton, Massachusetts** (OMNI, 1986) has regulations governing the emissions from solid fuel burning devices. The regulations are designed to limit visible smoke emissions to 60 percent opacity, except for a 15 minute start-up. Penalties range as high as $500 for a second offence. Woodstove users within the City of **Amherst, Massachusetts** are required to have an operator's licences (as of October 1, 1986). The licence exam is based upon the safe and effective use of woodstove.

The village of **Great Neck Plaza, New York** has a local law which prohibits the future installation and use of open-flame woodburning fireplaces.

Alberquerque, New Mexico (Burton, 1984) has a voluntary curtailment of residential wood combustion sources when ambient carbon monoxide concentration reach specified levels. The city has installed what is termed a "Pollution Signal Light" at the top of a tall building within the commercial area. The light's colour is changed depending on hourly CO concentrations, and citizens are asked to limit the use of automobiles and woodburning accordingly.

Lake Tahoe region (Nevada and California) in 1984 adopted an air quality regulatory plan (interim standard) (OMNI, 1986). The plan encourages the installation of new technology woodstoves. Placer County Air Pollution District (Squaw Valley Area) in 1986 were in the planning stages of adopting woodstove certification program for both conventional and catalyst - equipped woodstoves.

Washoe County, Nevada (Reno) has adopted regulations as a part of a plan to achieve National Ambient Air Quality Standard for CO. The Emergency Episode Plan (amended Sept. 26, 1984) established episode criteria as follows (OMNI, 1986):

EPISODE CRITERIA LEVELS

Pollutant	Averaging Time	Health Advisory	Stage 1 (Alert)	Stage 2 (Warning)	Stage 3 (Emergency)
Carbon Monoxide	8 hours	12.0 ppm	15.0 ppm	30.0 ppm	40.0 ppm
Ozone	1 hour	0.16 ppm	0.20 ppm	0.40 ppm	0.50 ppm
Suspended Particulates	24 hours	300 $\mu g/m^3$	626 $\mu g/m^3$	875 $\mu g/m^3$	

Effective November 1, 1987 all new homes can have only certified stoves installed. The County have initiated an extensive public awareness campaign to promote efficient woodburning practices.

2.3 SUMMARY

The range of woodstove regulations (existing and proposed) in place in the U.S. include a wide variety of approaches. The regulations and practices have been described in some detail in order to provide specific guidance in the event Ontario wishes to develop similar regulations.

3 SOURCE AND EMISSIONS CHARACTERIZATION 3-1

3.1 GENERAL OVERVIEW OF FACTORS AND EFFECTS ON EMISSIONS 3-1

3.2 FUEL CHARACTERISTICS 3-1

3.3 OPERATING CONDITIONS 3-5

3.4 SOURCE TESTING 3-5

3 SOURCE AND EMISSIONS CHARACTERIZATION

3.1 GENERAL OVERVIEW OF FACTORS AND EFFECTS ON EMISSIONS

In all combustion processes, both physical and chemical factors (variables) affect the efficiency of combustion and also the emissions produced by the combustion process. As the number of variables affecting the conversion to energy increases, efficiency invariable decreases. Wood combustion is based on the most common exothermic process, in which carbon is oxidized to CO_2 by oxygen.

Wood consists of cellulosic material in which there are a wide range of oxygenated and hydrocarbon type organic compounds. Not surprisingly, alteration of the combustion conditions results in a myriad of byproducts including: carbon monoxide, particulate matter and a wide spectrum of organic species of which polycyclic aromatic hydrocarbon species (PAHs) are of greatest concern.

The factors that affect the combustion most are:

a) rate of oxygen supply - ventilation
b) rate of carbon supply - batch size, fuel composition, fuel type
c) temperature - stove characteristics, operating conditions

The other factor that affects the efficiency of combustion is temperature. These factors are identified with respect to the characterization of emissions from residential woodstoves in the following subsections.

3.2 FUEL CHARACTERISTICS

Aside from the numerous varieties of wood fuels, commercially produced newspaper logs, cardboard logs, compressed wood (with and without binders), treated wood, peat and bituminous coal are used to fuel stoves on the North American continent. The conditioning process of these fuels is a significant factor in determining the efficiency of the heating device and the emissions produced.

In Ontario, alternate fuels used to heat residences generally are limited to a few species of woods, namely:

Region	Wood Types Used
Northwestern Ontario	Birch, jack pine, spruce
Central Ontario	Sugar maple, birch
Eastern Ontario	Birch

While newspaper logs and cardboard logs are used occasionally for ornamental fires in fireplaces, these fuels are extremely high in price and, hence, are not used for prolonged, nor intensive fuel combustion. For these reasons, discussion of fuels will be limited to commonly available wood types.

Soft and hard wood types generally have different heating values due to different composition, structure and density. Total particulate emissions by fuel type have been found to vary from 8.9 g/kg to 29 g/kg (Hartman and Rives, 1985). A typical emission rate for non-certified conventional woodstoves is around 20 g/kg (tested using Oregon/EPA Certification) (personal correspondence with J. Core). Fuel type effects also are dependent on burn-rate and, hence, in most studies, the variability caused by other effects within the same fuel type group has been overshadowed by factors such as stove type (Hartman and Rives 1985; Shelton and Gay, 1986). The study by Muhlbaier (1981) of emissions, from two softwoods and five hardwoods also confirmed this phenomenon. Typical particulate emission results (maintaining other variables of combustion as constant as possible) were:

•	softwoods	11.9 ± 2 g/kg
•	hardwoods	10.4 ± 2 g/kg

Surface Area

The log surface area is dependent on log size and geometry. Round logs with large diameter have the smallest surface area to mass ratio, in comparison with split logs and quartered logs. Emissions from residential wood combustion (RWC), therefore, also are influenced by log size and geometry. This effect has been explored by several researchers (Hubble et al., 1981; Cooke et al., 1982; Muhlbaier, 1981). Results indicated that particulate and organic emissions were considerably higher for the larger logs with smaller surface area to mass ratios (Muhlbaier, 1981). However, CO emissions increased drastically with an increased surface area to mass ratio (Cooke and Allen, 1982) from 20 (lb/1000 lbs of wood) to 110 (lb/1000 lbs of wood) for surface area to mass ratios of 10 ft^2/ft^3 to 40 ft^2/ft^3, respectively.

Moisture Content

The moisture content of fuel wood has been known to influence the rate of combustion and the resultant emissions since man discovered fire. This factor of combustion has been studied extensively, and a good insight to the effects of moisture is presented in the following table (Weston, 1989).

As evident in Table 3.1, particulate emissions increase significantly with increased moisture within the fuel wood. This effect is especially emphasized when values are normalized to the actual heat gained by the combustion process.

TABLE 3.1

Impact of Moisture on Wood Net Heat Content and Particulate Emissions[1]

Wood Moisture* Content (%)	Relative Energy Content	Relative Particulate Emissions Per Pound Wood Burned	Relative Particulate Emissions Per Net BTU Content of Wood Burned
10%	1.00	1.0	1.00
20%	.88	1.2	1.36
30%	.67	1.5	2.25
40%	.59	1.9	3.22
50%	.47	2.4	5.10

* Wet basis, i.e., 10% moisture content = $\frac{\text{10 lb. water}}{\text{10 lb. water + 90 lb. wood}}$

[1] From Weston, 1989

3.3 OPERATING CONDITIONS

Operating conditions of the woodstove influence the combustion temperature and consequently the emissions generated. The study of the relationship between operating conditions and the resultant emissions is complicated by the stages of burning (burn cycle) (Hayden and Braaten, 1985), the stove type (Shelton and Gay, 1986), and the energy demand (heat required in relation to stove efficiency and rate of burning). The resultant physical factors produced by the above variables of combustion have been studied by numerous investigators and have been summarized in a concise diagram by Hubble et al., (1981) presented as Figure 3.1. The resultant emissions are highly dependent on these physical factors and these have been summarized for various stove types by Kowalczyk, Bosserman and Tombleson (1981).

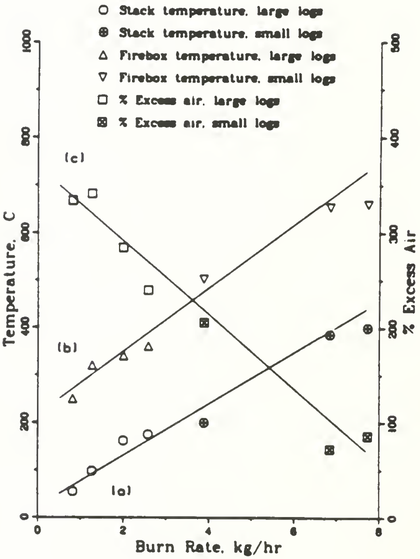
3.4 SOURCE TESTING

The need for a standard source testing method was clearly recognized by the U.S. EPA and the standard EPA Methods 5G and 5H were developed for woodstove testing. While information exists for various airtight stoves, catalytic stoves, and the prototype wood pellet stoves, each stove type is unique in terms of characterization of emissions. Chemical characterizations of the RWC source generally have employed the specific test conditions of EPA modified Method V to identify the effect of factors such as wood type (e.g., oak or fir), and size of wood logs (6 inch diameter) with a common box type airtight stove (Rau, 1988).

Unfortunately, these test conditions do not reflect the actual conditions of RWC in Ontario. Firstly, the wood types used in the source characterization test performed to date are not in common use in Ontario. Oak is a comparatively expensive type of wood in Ontario and very little fir is grown because of local climate. Another variable that has not been addressed in the literature reviewed are emissions from Canadian manufactured woodstoves. Two very common types of woodstoves employed in Ontario are Kerr Titan and Fawcett WF 200.

FIGURE 3.1

Summary of Stack Temperature [curve (a)], Firebox temperature [curve (b)], and % Excess Air [curve (c)] versus Burn rate from Combustion of 0.12 -m- and 0.06 -m- Diameter Oak Logs.



Methods for source sampling of woodstoves for particulate emissions and organic compounds have been standardized (Cooke et al., 1984). The focus of the methodology is to quantify emissions from a specific stove type under rigorously defined conditions. The general methodology employs a standard type air-tight stove, with a sampling port that enables a sampling probe to collect a representative sample of the resultant mixture of flame gases and suspended particulate matter (Allan et al., 1984). The following conditions have been standardized:

- wood species, size and shape (oak logs, 20 cm diameter);
- moisture content (20% W/W wet basis);
- minimum burn time;
- minimum sampling time;
- fuel charge weight (10 kg, dry);
- sample size (3 m^3 (STD, dry)); and
- steady-state operation.

While the purpose of standardizing these factors is to facilitate comparison between emissions from different stove types, these conditions do not reflect actual operating procedures and practices, local climate or local fuel wood types used.

The EPA emission factors discussed earlier are based on average values obtained through the standard testing procedure, conducted in various climatological locations. While these emission factors allow for an estimation of national emissions in the United States, their representativeness and applicability have been under review by the Inventory Management Division of Environment Canada. It was concluded that further work is required to quantify emission factors that reflect regional and temporal variability characteristics of Canadian Climates (Yandle, 1989) and wood fuels.

An average source profile for residential woodstoves has been compiled by several investigators in the following locations: Medford, Oregon, Portland/Seattle and Pocatello, Idaho. These profiles have been provided by J. Core and are included in Appendix A, however, the aforementioned conditions and limitations restrict the usefulness and applicability of these profiles.

4 AMBIENT MONITORING METHODS TO DETERMINE RWC AIR QUALITY 4-1

4.1 SAMPLING OF PARTICULATE PHASE SPECIES 4-2

4.2 SAMPLING OF VAPOUR PHASE SPECIES 4-4

4.3 COMBINED PARTICULATE AND GASEOUS SAMPLING 4-6

4 AMBIENT MONITORING METHODS TO DETERMINE RWC AIR QUALITY

A variety of objectives have motivated ambient air quality monitoring studies in areas with RWC impacts. One of the major objectives has been to determine the contribution of RWC emissions to ambient air quality - especially in regions with poor air quality (where existing ambient air quality standards are exceeded). Often, there are parallel studies for indoor monitoring to determine exposure of inhabitants while indoors, source characterization of emissions, as well as parallel surveys to determine wood consumption. Samples collected are analyzed for elemental species, ionic species, carbon analyses (C-14 isotopic composition, volatilizable (C_{vol}) and elemental carbon (C_{el})), a wide range of organic compounds - usually classified into polynuclear aromatic compounds (PAH), volatile organic compounds (VOC), as well as for the traditional pollutant gases (especially CO and NO_x). Recently, monitoring to determine the mutagenic activity of samples dominated by RWC emissions has been conducted.

Methods used to collect and analyze ambient samples that are impacted by RWC emissions are summarized in this chapter. The methods for the sampling and analysis of indoor levels and for source characterization are excluded.

Depending on the study objectives, sampling methods collect material for elemental (mainly inorganic), organic or biological data in three phases or modes:

1. particulate fraction;
2. gaseous fraction; and
3. combined particulate/gaseous fractions.

The sampling and to a lesser extent, analysis techniques that are used to determine ambient RWC impacts depend on the fraction required hence it is convenient to discuss methods for the collection of material in these phases.

4.1 SAMPLING OF PARTICULATE PHASE SPECIES

Sampling methods for ambient suspended particulate material commonly employ filter impaction of a known volume of air drawn through the filter matrix. Sampler types used include high volume samplers with or without size selection, and dichotomous samplers.

High volume samplers collect total suspended particulate matter, i.e., a full size range considered to contain particles of aerodynamic diameter 100 µm and less. Sampling rates are typically 1.13 to 1.70 m^3/min (40 to 60 ft^3/min). Samples generally are collected over a 24-hour period although some studies have used 12-hour (day/night sampling) sampling periods. Since particulate emissions from RWC appliances are predominantly in the 0.1 to 1.0 µm diameter size range (e.g., Kowalczyk and Greene, 1981), size selective sampling is often employed for ambient monitoring of RWC impacts. With the aid of a size selective inlet, high volume samplers collect suspended particles with a predetermined maximum cut-off diameter, typically 10 µm. When fitted with cascade impactors, high volume samplers collect particles in a number of particle diameter size ranges typically ~0.5 to 10 µm. Other samplers involving collection of particles on filter media, are in use and employ lower flow rates (low and medium volume samplers) with size selection of particles.

Dichotomous samplers have been the samplers that have been employed frequently in monitoring programs associated with the assessment of ambient RWC impacts. These samplers collect particles in two size ranges, usually < 2.5 µm (the fine or inhalable fraction) at (usually) 1.67 L/min, and 2.5 to 15 or 10 µm diameter - the coarse fraction at flow rates of (usually) 15 L/min. However, a limitation of low volume sampling is the possibility of filters plugging up in areas of heavy woodsmoke impact. Low volume samplers that have been used in the study of residential wood combustion include:

- IMPROVE samplers for PM_{10} and PM_{25}; and
- "survey" samplers (inexpensive, battery powered).

The USDI National Park Service employ the IMPROVE samplers for PM_{10} and PM_{25} monitoring, and the U.S. EPA Region X uses the battery operated "survey" samplers which are similar to the personal pumps which are commonly used for industrial hygiene studies.

In areas of high RWC impact where the aerosol loadings render low volume sampling ineffective, medium volume samplers have been employed. Virtually all of the RWC studies conducted in Oregon were conducted using medium volume (4CFM) samplers. The design of the samplers is a sequential sampler with 12 sampling ports that draw the ambient air sampling through a Sierra-Anderson 254 PM_{10} inlet capturing the fraction below 10µ by iimpaction on Teflon or quartz filters. This sampling method has been approved as a PM_{10} equivalent method by the U.S. EPA.

Mass is determined by a gravimetric difference.

The filter media employed in the samplers are usually those that provide low background (blank) levels of metals and organics. For mass and organics determinations, glass fibre filters have been used in high volume samplers. Teflon or quartz filters are used for mass and inorganic analyses. Teflon impregnated glass fibre filters (e.g., Pallflex TA60A20) or quartz filters are suitable for carbon analyses and bioassay analyses. Teflon filters (typically 1 - 2 µm pore diameter) have been used nearly exclusively in dichotomous samplers. The Teflon coated glass fibre or Teflon filters provide suitable blank levels for the determination of metals, ionic inorganic species as well as organics.

The current protocols use either Teflon (for mass and XRF analysis) or quartz filters (for ion analysis, organic/elemental carbon and organic compound analysis).

Nephelometers

Because the particulate emissions resulting from wood burning are very fine, there is the potential for longer suspension times and increased light scattering by the fine particles suspended in ambient air. Aside from the obvious health implications that can result, a deterioration of visibility occurs. Visibility is of particular concern in resort areas, areas of special natural beauty and locations where vision impairment can limit other activities such as air transportation.

A measure of the degradation of visibility due to fine suspended particles can be assessed visually or may be obtained using a nephelometer. Nephelometers do not measure the concentration or size of the particulate matter but rather the degree of light scattering that is produced.

The light scattering coefficient b_{scat} can be monitored continuously, regardless of cloud cover or darkness.

4.2 SAMPLING OF VAPOUR PHASE SPECIES

The collection of vapour phase compounds is complicated by several factors:

- volatility;
- reactivity;
- break-through threshold; and
- stability of and consistency of sampling medium.

Gaseous compounds are not efficiently collected using filter paper impaction and adsorption; instead, actual volumes of air are collected, or alternatively, the vapour phase compounds are absorbed onto media that retain gaseous compounds with integrity over time. Sampling methods that have proven successful for gaseous compounds are:

- adsorbent tubes;
- tedlar bags;
- stainless steel canisters;
- direct cryogenic trapping; and
- impinger trains (generally used for source sampling).

Adsorbent tubes have been used extensively and the medium commonly used to adsorb low molecular weight hydrocarbons is activated charcoal. For a wider range of organic compounds, sorbent tubes are packed with tenax, carbosieve (molecular trap), fluorosil etc.; either exclusively or in combination. Since flow rate influences collection, and non-linearity and breakthrough occur in the high concentrations, the sampling protocol specifies up to four tubes be exposed in parallel. The quadruple sampling and analysis renders this method of sampling as costly, in comparison to Tedlar bags and canisters.

Tedlar bags are available in various volume sizes and are employed for grab sampling of a representative air mass. While this method is relatively inexpensive, the samples are extremely unstable and require immediate analysis. Aside from the reaction of the constituents sampled, compounds react with the interior surface of the bag. Since a comparatively small volume of air is sampled, two inherent problems result:

1. The sample may not be representative of the air mass.

2. Concentrations are low and subsequent sensitivity problems in analysis may result in levels below or near the detection limit.

Presently the U.S. EPA protocol for sampling organic and trace toxic gases employs pre-evacuated stainless steel canisters. The initial cost of the canisters is greater than other sampling methods, however, these canisters may be purged and reused. The canisters are filled with ambient air at a known flow rate to a pressure of approximately 1 atmosphere over a 24 hour sampling period. The spherical design of the canisters along with the inert qualities of stainless steel in combination with most non-acidic gases, minimizes chemical reactions and wall effects.

Cryogenic trapping has been used to preconcentrate vapour phase samples, however, the equipment is generally too cumbersome to move from the laboratory bench to the field. One automated GC with a cryogenic trapping device is available from Andersen instruments for field measurements. The sensitivity is such that this method can be used as a preliminary, qualitative evaluation of ambient air quality. Another drawback is the necessity for *a priori* knowledge of the compounds of interest for proper column selection.

4.3 COMBINED PARTICULATE AND GASEOUS SAMPLING

Several studies have been undertaken to determine the vapour particle distribution in Hi-Vol sampling (Cautreels and Van Cauwenberghe, 1977: Galasyn et al., 1984; Thrane and Mikalsen, 1981; Yamasaki et al., 1982; Davis et al., 1983; Dann et al., 1989) and also in low volume sampling (Bjorseth and Eklund, 1979; Andersen et al., 1988; Otson and Hung, 1983).

The distribution ratios of particulate to gas phase concentration of several PNA's as well as other classes of organics were reported by Cautreels and Van Cauwenberghe. For phenanthrene, anthracene, methylpyrene and methylanthracene, the distribution factors were 0.027 to 0.088; thus most of these compounds are in the gas phase. Fluoranthene (F), pyrene (P) and benzofluorenes had intermediate values 0.26, 0.49 and 1.25 respectively while benzo(a)anthracene (BaA), chrysene (CHR), benzo(k)fluoranthene (BkF), benzo(b)fluranthene (BbF), benzo(a)pyrene (BaP), benzo(e)pyrene and perylene (PY) were primarily in the particle phase with distribution factors ranging from 3.14 to 11.5.

Two basic methods for sampling both particulate and vapour phase compounds exist:

- high-volume sampling with adsorbent backup cartridge; and
- a modified EPA method 5 filter/impinger sampling train.

The high volume sampler with a backup sorbent has the advantages of being easy to operate, sampling a large volume of air, low blank values, and has a 24 hour sampling time. Impinger trains involve much cumbersome equipment and hence are generally used for source sampling rather than ambient sampling. Several high volume/backup sorbent options are discussed below.

Distribution factors for several PAHs were obtained by Thrane and Mikalsen (1981), using glass fibre filters and serial polyurethane foam plugs (PUF); and by Cautreels and Van Cauwenberghe using glass fibre filters and backup Tenax sorbent at the same sampling location. Better collection efficiency of PUF was indicated, but the authors expressed concern that back diffusion of volatile compounds from the PUF to the filter may occur during the post-sampling/pre-analysis period.

PUF, XAD-2 and Florisil were evaluated as back-up sorbents for Hi-Vol sampling for PAH (Davis et al., 1983). The percentages of the total PAH catch of fluoranthrene, pyrene, benzo(a)pyrene, 3-methylcholanthene, benzo(ghi)perylene and 1,2,4,5-dibenzopyrene retained on the filters ranged from 11 to 23, 11 to 30, 54 to 99, 55 to 94, 54 to 77 and 64 to 92% respectively.

Galasyn et al. (1984), however, used quartz filters and a PUF backup sorbent and found no detectable BaP on the sorbent. Also, less than 10% of phenanthrene and anthracene were retained on the filter, while fluoranthrene, pyrene, BaA and Chr were retained on the filters. The fractions retained on the filter were lowest in the winter samples.

Extraction of the sample may involve a combination of methods (Soxhlet, ultrasonification, sublimation, thermal desorption) and different extraction solvents (benzene, toluene, methanol, ethanol, methylene, chloride, etc.) depending on the compounds of interest. Sequential extraction is necessary when a wide variety of compounds are sought.

Analytical Methods

The material collected on filters are analysed for elemental constituents - i.e., inorganic species, ionic species or organic compounds. Most studies associated with assessing RWC impacts have analysed inorganic species together with organic carbon (total organic and occasionally inorganic carbon). Monitoring methods using the dichotomous samplers have relied mainly on X-ray fluorescence (XRF) or neutron activation analysis (NAA) for elemental analysis.

The solid matter impacted onto the filter medium is extracted from the filter using a solvent such as dichloromethane (Steiber and Dorsey, 1988) hexane, cycloheptane etc., or acidic solutions (for metals). Greatest progress in improving analytical resolution and reproducibility has been in the selection of extraction solvent and successive extraction strategies. The resultant solution can be analyzed for metals using Atomic Adsorption (AA) techniques. Elemental analysis can be performed using neutron activation analysis (NAA) or X-ray fluorescence (XRF) or X-ray fluorescence without filter extraction. Organic constituents adsorbed onto the surface of the particulate matter can be extracted and analyzed using gas chromatography coupled with mass spectroscopy (GC/MS) techniques.

Extraction from dichotomous filters generally follow the same procedure outlined for high volume filters of various materials. Since the surface area and pore size of teflon dichotomous filters are smaller compared with glass fibre or quartz fibre filters used in high volume sampling, a smaller volume (low-volume) of air is sampled, and generally the sample is less concentrated. For most sampling programs, dichotomous Teflon filters can be analyzed by Atomic Absorption Spectroscopy (AAS), ion chromatography (IC), thermal optical reflectance (TOR). In some cases, more sensitive methods of analysis are desirable, such as neutron activation analysis (for elemental composition), and gas chromatography with mass spectroscopy (GC/MS), for organic and inorganic compounds.

Ambient concentrations are generally in the range of parts per billion (ppb) and thus, highly sensitive methods of analysis are required. Analytical methods commonly used to determine ambient concentrations include:

- gas chromatography (GC);
- gas chromatography with mass spectroscopy (GC/MS);
- ion chromatography (IC);
- high performance liquid chromatography with ultraviolet fluorescence (HPLC/UV-fluorescence);
- atomic absorption (AA);
- inductively coupled plasma (ICAP);
- thermal optical reflectance (TOR);
- neutron activation analysis; and
- X-ray fluorescence.

These methods of analysis and their application are summarized in the following paragraphs.

Gas Chromatography (GC)

A gas chromatograph is a sensitive instrument based on differing retention times of compounds on a column of appropriate material at an elevated temperature. The unknown sample is introduced into a heated injection nozzle that volatilizes the sample and passes the sample through the column using an inert carrier gas. The material in the column differs for different suspected compounds. The compounds present in the sample will elute at different temperatures and times. The signal produced by the close detector (either FID or ECD) is a series of peaks. The area under the peak formed, is directly proportional to the concentration and is determined by integration.

This method of analysis is effective for the identification of volatile and semi-volatile compounds.

Gas Chromatography with Mass Spectroscopy (GC/MS)

The gas chromatograph sensitivity and compound identification capabilities are enhanced by injecting the column separated sample via a solid probe to a mass spectrometer. The sample is ionized and passes through a mass selective filter. The resultant mass spectrum can be used to resolve the compounds by matching characteristic known spectra. This is a highly sensitive method for resolving and determining concentrations of volatile and semi-volatile compounds.

Ion Chromatography (IC)

The basic concept of ion chromatography is to separate ions in solution and detect changes in conductivity. Both organic and inorganic ions can be analyzed by choosing an appropriate exchange resin in the IC column. The ion exchange column separates ions by size and charge. The order of elution from the column determines the ion and the change in conductivity quantifies the ion.

High Performance Liquid Chromatography (HPLC)

HPLC analysis is a highly efficient analytical technique for a wide variety of compounds, including compounds difficult to distinguish using GC techniques. These include polar compounds, compounds of high molecular weight and compounds that are not readily thermally desorbed (i.e., relatively non-volatile compounds). The high pressure liquid chromatography system can be used in conjunction with various detectors. The UV-fluorescence detector can produce highly sensitive results in the order on nanograms and subnanograms depending on the compound. This method (HPLC/UV-fluorescence) is particularly effective for the analysis of Polynuclear Aromatic Hydrocarbons (PNA, PNAH or PAH).

Atomic Absorption (AA)

Upon excitation, metals radiate ionic and atomic spectral lines of excellent resolution and reproducibility. Atomic Absorption employs this characteristic of metals, by providing the exact spectrum of excitation energies via a metal specific lamp under excitation. The energy is absorbed by the non-excited atoms in the sample. A detector measures the amount of energy absorbed, and the concentration of the element in the sample is proportional to the absorption.

In the analyzer, a small amount of extracted sample is aspirated into a flame, and the radiating light beam is produced by a lamp specific to the metal to be analyzed. This method is sensitive to a few parts per billion for most metals, and has been used extensively to quantify metals in TSP samples in the U.S. and Canadian national air quality monitoring programs (AIRS and NAPS).

Inductivity Coupled Argon Plasma (ICAP)

The basic principle of unique excitation energies and ionic emissions are employed in ICAP. An argon plasma flame is used to excite the atomic and ionic electrons. The energy emitted upon return to rest-state is measured by a photomultiplier tube. The advantage of this method of analysis for metals over AA, is that several metals can be analyzed at one time. Resolution does become a problem with similar spectral profiles. The sensitivity is generally comparable with AA techniques.

Neutron Activation Analysis (NAA)

Neutron Activation Analysis is a highly accurate method of determining elemental composition. The sample is irradiated with a neutron flux to create radioactive or unstable isotopes. As the unstable isotope decays, a variety of nuclear particles are emitted. Commonly, the gamma-ray spectrum is measured for its ease of detection. The number of scintillations per time interval and the energy level of the scintillations produce an element specific spectrum. Detection limits depend on the period of irradiation and the decay process of the element, and range upwards from several atoms per sample.

The limitations of NAA lie in the inability to distinguish molecular species. Thus for samples which are intended to quantify RWC, only the elemental concentrations can be obtained.

X-Ray Fluorescence (XRF) and Particle-Induced X-Ray Emission (PIXE)

Atoms exhibit fluorescence in the X-ray region of the spectrum upon irradiation with X-rays (XRF) or with a beam of particles - protons usually, or alpha particles (PIXE). X-ray fluorescence results also from the use of electron beams to bombard the sample and this principle is used in scanning electron microscopy coupled with XRF instrumentation. The emitted X-rays are characteristic of the element and the intensity of the emission is related to the amount of the element present. The XRF and PIXE techniques are suitable for elements with atomic weights above aluminum since there is considerable air absorption of the fluorescence from the lighter elements. The advantage of this method above NAA is that the cost of analysis is significantly lower.

Carbon Analyses - Thermal Optical Reflection (TOR)

Organic and elemental carbon are measured by thermo-optical carbon analysis technique (Huntzicker et al., 1982; Stevens, 1985). For the (volatilizable) organic carbon determination, the filter is heated in a pure helium atmosphere at temperatures of 300 to 600°C. Volatilized carbon is converted to CO_2 in a MnO_2 oxidation oven. The CO_2 is then reduced to CH_4 in a Ni-firebrick methanator. The CH_4 is measured by gas chromatography using a flame ionization detector.

Elemental carbon is then removed by heating in a 2% O_2 -98% He atmosphere at 400 to 850°C and treating the CO_2 produced as for the organic carbon. During the removal of the volatile (organic) carbon, some of the volatile carbon is pyrolyzed to elemental carbon. In order to correct for the elemental carbon so produced, the reflectance of the filter is continuously monitored (using a 633 nm He-Ne laser) during the heating processes to remove elemental carbon. The amount of elemental carbon oxidation necessary to return the filter to its initial reflectance value (i.e., before conversion of organic carbon to elemental carbon occurred) is used to correct the elemental carbon value measured.

The methods of sampling and analysis commonly used have been described separately in this section. Clearly, the choice of sampling technique, sampling medium and analytical method must include compatibility of all three facets in order to provide results of accuracy and integrity. An integrated approach to system design is vital to any ambient air study and is particularly crucial when attempting to resolve similar sources to a composite sample.

5 IMPACT ASSESSMENT STUDIES FOR RESIDENTIAL WOOD COMBUSTION 5-1

5.1 SUMMARY OF SELECTED IMPACT STUDIES TO CHARACTERIZE RWC IMPACTS 5-2

5.2 SUMMARY 5-16

5 IMPACT ASSESSMENT STUDIES FOR RESIDENTIAL WOOD COMBUSTION

This section presents a summary of various types of monitoring studies in which the ambient air quality impacts of RWC have been determined. The studies summarized indicate the potential for adverse air quality impacts from RWC. Emphasis has been placed on describing studies for locations that are climatically similar to Ontario.

Studies to evaluate the impact of emissions from residential wood combustion initially examined the particulate emissions in the fine size fraction (0.01 to 1.0 μm) since source testing information indicated that most (> 90%) of the particulate emissions from RWC were in the fine fraction (Muhlbaier, 1982). Airshed studies focused on upwind/downwind mass loadings in the fine fraction. This was frequently accompanied by questionnaires addressing burning practices of the homes sampled. The need for better source resolution is evident, since all combustion sources display similar particle size distributions. Subsequent studies have followed the following designs:

a) upwind/downwind with particle sizing and chemical analysis;

b) outdoor sampling with source apportionment (using inorganic and organic woodsmoke characterizations); and

c) tracer studies.

Impact Studies In the United States

During the late 1970's and 1980's the rise in interest in RWC and the accompanying environmental concerns prompted air monitoring studies in several areas of suspected impact. Issues of non-attainment of aerosol and CO objectives prompted federal action to investigate the effects of residential wood combustion in various US EPA programs.

The major pre-1985 U.S. studies have been reviewed with respect to strategy and methodology employed in an EPA study (Hartman and Rives, 1985). This information is summarized in Table 5.1 in this report.

Ambient data from the major RWC studies were compiled in a Technical Support Document (EPA-450/4-85-012). The ambient air quality data are summarized with references, in Tables 5.2 - 5.5. As indicated in Table 5.2, average RWC impact determined in these studies was estimated for the fine mass fraction. The percentage contribution of RWC to the fine fraction ranged from 1.5% to 72.8%. Average ambient concentrations (Table 5.3) of carbon monoxide ranged between <1 ppm to 2.7 ppm (8 hour average). Of major concern in RWC studies, has been the incremental burden of benzo(a)pyrene (BaP) caused by woodsmoke emissions. Ambient BaP levels in one U.S. location was found to be above 100 ng/m^3 (Table 5.4).

An elaboration of selected RWC studies is provided in the following subsections.

5.1 SUMMARY OF SELECTED IMPACT STUDIES TO CHARACTERIZE RWC IMPACTS

Integrated Air Cancer Project (IACP)

The IACP program is an interdisciplinary approach to identify principal carcinogens in ambient air and to investigate the relative source contributions of these compounds. In the initial phase of the program, the focus of investigation was small combustion sources. In particular, residential wood combustion and vehicular exhaust were examined in various airsheds. Air monitoring was conducted in Raleigh, NC; Albuquerque, NM; and Boise, ID; (Highsmith et al., 1987; Highsmith et al. 1988; Highsmith et al., 1988a; Stevens, 1985; Zweidlinger, 1987, 1988).

The experimental approach of these studies involved sampling at the source, parallel indoor/outdoor measurements (particulate matter, trace organics, VOC, PAH, etc.) and included the use of dispersion and receptor models to resolve the woodsmoke contribution.

TABLE 5.1

Major U.S. Airshed Studies and Impact Assessment Methods* (pre 1985)

	TSP	<2.5µm	POM	Upwind/ downwind	Teflon filter	Glass fibre filter	Backup trap XAD-2	Other filter	C14	CMB	K:Fe	Survey	Stove test	TSP average µg/m3
Colorado, Denver "Brown cloud"	X	X		X	X	X					X			89.6
Colorado, Telluride	X		X	X		X								61
New Hampshire, Lyme Center	X		X	X		X						X		52
Alabama, Petersville	X	X	X	X		X	X		X	X				N/A
Montana, Missoula	X	X			X	X				X	X		X	81
Oregon, Medford	X	X	X			X		X	X	X	X		X	100
Portland Aerosol Characterization Study (PACS) (1979-80)	X	X		X		X		X	X	X	X		X	75

* Source: Hartman and Rives, 1985

TABLE 5.2

Summary of Air Quality Data from RWC Studies in the U.S.

No.[a]	Location, State	Samples		Site		Avg RWC Impact on Fine Mass <2.5 μm	Avg Fine Mass From All sources <2.5 μm	Avg RWC Fine Mass Impact[b] <2.5 μm	24-hr Max RWC Fine Mass Impact[c] <2.5 μm	Avg PM_{10} or PM_{15} Mass ($\mu g/m^3$)	Avg TSP Mass ($\mu g/m^3$)	Reference	Comments
		No.	Dates	Name	Type								
1	Waterbury, Vt	33	1979/80	Eldredge	(R)	35.0[d]	-	27.0[d]	-	-	79	Sanborn et al, 1981	Seasonal average impact estimates based on dispersion model
		39	1980/81	Eldredge	(R)	35.0[d]	-	18.9[d]	-	-	54		
		33	1981/82	Eldredge	(R)	65.0[d]	22.0	18.7[d]	29.9[d]	26.0	35	Sexton et al, 1983, 1984	
2	Western, MA	13	12/81 - 4/5/82	Springfield	(C)	-	-	15.0[d,e]	25.0[d,e]	39.0	59	Howland and Kowalczyk, 1984	CMB analysis, seasonal impact
		13		East Hampton	(R)								
3	Nashville, TN	24	1-3/83	Center City	(C)	33.9	25.4	8.6	51.2	65.5	72	Imhoff et al, 1984	CMB analysis, seasonal impact
		8		Center City	(R)	22.7	22.5	5.1	-	47.3	57		
		7		Background	(B)	45.0	27.8	12.5	-	48.8	49		
		12		Center City	(R)	66.2	29.9	19.8	26.9	59.7	84		
4	Petersville, AL	8	2/2-2/14 1981	Downwind	(R)	73.7	45.3	33.4	65.1	-	-	Imhoff, 1982	CMB analysis, seasonal impact
5	Albuquerque, NM	56	12/28/82 to 2/23/83	Zuni Park	(R)	66.8	37.7	25.1	59.3	60.9	-	Zak et al, 1984	MLR results, seasonal study
6	Missoula, MT	12	2-3/83	Lyons Park	(R,C)	58.7	63.0	37.0	48.0	111.0	186	Cooper and DeCesar, 1989	CMB analysis, seasonal study
7	Denver, CO	16	12/7-19 1978	Five Sites Composite		14.0	39.5	5.5	-	-	90	Wolf et al, 1980	CMB ^{14}C results on composites
		5				-	-	18.0[d]	29.0[d]	-	-		
8	Telluride, CO	13	1/7-1/9 1980	Site 1	(B)	-	-	5.2[d]	13.6[d]	-	20	Murphy et al, 1982	TSP samples, RWC impact estimated from B(a) P levels, seasonal study
				Site 2	(C)	-	-	29.6[d]	59.3[d]	-	61		
				Site 3	(R)	-	-	9.6[d]	20.4[d]	-	36		
				Site 4	(B)	-	-	-	-	-	8		
				Composite		-	-	35.6[d]	-	-	71	Wilson et al, 1983	Based on SF_6 tracer study
9	Reno, NV	8	2-3/84	Three Site	(RCR)	-	-	13.4[d]	23.0[d]	-	83	Bonderson, 1984	RWC impact estimated on TSP filters
10	Las Vegas, NW	4	12/83	E Charleston	(C)	50.0[d]	-	-	41.1[d,h]	-	140	Naylor, 1984	Mass measurements estimated

TABLE 5.2 (cont'd)

Summary of Air Quality Data from RWC Studies in the U.S.

No.[a]	Location, State	Samples		Site		Avg RWC Impact on Fine Mass <2.5 µm	Avg Fine Mass From All sources <2.5 µm	Avg RWC Fine Mass Impact[b] <2.5 µm	24-hr Max RWC Fine Mass Impact[c] <2.5 µm	Avg PM_{10} or PM_{15} Mass (µg/m³)	Avg TSP Mass (µg/m³)	Reference	Comments
		No.	Dates	Name	Type								
11	Boise, ID	9	12/80-2/81	Fairview, & Liberty St.	(C)	69.5	121.8^e	84.7^e	$127.9^{e,j}$	122.0	149	Core et al, 1984	All analyses on PM_{10} samples
12	Portland, OR	32	1977-78	Flavel Park	(R)	18.6	19.9^j	3.7^f	47.4^i	64.0	65	Cooper and Watson, 1979; Watson, 1979	Annual averages, seasonal averages are higher
		32		Indus Air	(I)	8.9	27.3^j	2.7^f	49.5^i	62.0	79		
		32		Downtown	(C)	18.4	23.8^j	3.9^j	31.8^h	64.0	77		
		32		Carus	(B)	8.6	15.6^j	1.5^j	7.3	29.0	33		
		18	1977-78	Downtown	(C)	42.0	22.7	9.5	24.2	-	-	Shah, 1981, Shah et al, 1984	Reanalysis of above data
		8	1-3/81	Whitman Sch.	(R)	68.5	40.0	27.4	49.0	-	62	Core et al, 1984	CMB analysis
13	Medford, OR	40	4/79 to 3/80	Justice Bldg	(RC)	65.7	46.0	30.2	126.0^j	-	97	DeCesar and Cooper, 1981	Annual average impact from CMB analysis
		40		Dodge Rd.	(B)	58.7	15.0	8.8	33.0	-	26		
		40		White City	(I)	42.2	32.0	13.5	80.0	-	94		
14	Yakima, WA	4	11/17/80 2/21/81	Courthouse	(C)	93.1	53.8	50.0	55.1	-	222	Core et al, 1984	CMB analysis, seasonal average
15	Spokane, WA	15	1-3/81	Country House	(R)	81.0	55.0	44.5	-	-	119	Core et al, 1984	CMB analysis, seasonal average
		1	10/31/80	Country Health	(C)	04.7	53.0	34.3	-	-	-		
		4	1-3/81	Crown Zellerbach	(I)	45.3	37.0	18.7	19.1	-	232		
16	Seattle, WA	8	2-3/81	Newport Bay	(R)	87.0	33.8	29.4	48.8	-	72	Core et al, 1984	CMB analysis
		2		South Park	(R)	65.8	-	-	-	-	-		
		3		Georgetown	(I)	73.4	39.7	29.1	35.5	-	-		
17	Tacoma, WA	4	1-2/81	Fire Station	(I)	74.9	47.0	35.2	44.3	-	159	Core et al, 1984	CMB analysis
18	Longview, WA	4	12/80-1/81	City Shops	(C)	81.4	41.8	25.6	40.5	-	-	Core et al, 1984	CMB analysis
19	Anchorage, AK	8	12/81-1/84	Composite Samples		-	-	17.5^d	45.0	-	45	Myers, 1984	TSP filter analysis

TABLE 5.2 (cont'd)

Summary of Air Quality Data from RWC Studies in the U.S.

No.[a]	Location, State	Samples		Site		Avg RWC Impact on Fine Mass <2.5 μm	Avg. Fine Mass From All sources <2.5 μm	Avg RWC Fine Mass Impact[b] <2.5 μm	24-hr. Max RWC Fine Mass Impact[c] <2.5 μm	Avg PM_{10} or PM_{15} Mass (μg/m³)	Avg TSP Mass (μg/m³)	Reference	Comments
		No.	Dates	Name	Type								
20	Juneau, AK	8	12/81	Floyd Dryden	(RI)	-	-	93.3	123.0[f]	-	104	Cooper and Frazier, 1983	High TSP days averages CMB analysis, seasonal impact
		11	12/82	Floyd Dryden	(RI)	-	-	48.4	234.0[g]	-	56		
		10	12/81	Super Bear	(R)	-	-	72.8	157.0[f]	-	87		
		9	12/82	Super Bear	(R)	-	-	56.1	168.0[g]	-	61		
		3	12/82	Municpl Bldg	(B)	-	-	9.5	-	-	15		

Abbreviations

C	-	Residential Wood Combustion
μm	-	Micrometers (Particle Diameter)
TSP	-	Total Suspended Particulate
PM10	-	Particulate Matter; particle diameter 10 μm
PM_{15}	-	Particulate Matter; particle diameter 15 μm
R	-	Residential land use predominates near site
C	-	Commercial land use predominates near site
I	-	Industrial land use predominated near site
B	-	Background site, remote from urbanized areas
CMB	-	Chemical Mass Balance
MLR	-	Multiple Linear Regression

Footnotes

a. Numbers correspond to profiles in Section V of this report
b. Average RWC impact % X Average Fine Mass
c. From Literature cited unless otherwise stated
d. Estimated as explained in text
e. Average impact measured on PH_{15} sample
f. Maximum impact on 11/19/82, not included in December average impact
g. Maximum impact on 11/22/82, not included in December average impact
h. 4-hour maximum impact
i. 8-hour impact
j. Annual impact

TABLE 5.3

Summary of RWC Carbon Monoxide Levels for Profiled Locations

Location, State	Sampling Period	Monitoring Site & Type	CO Levels in PPM 8 hr. avg.	8 hr. max.	1 hr. max.	Evidence of RWC Impact on CO	Reference
Waterbury, VT	1/31/80 3/12/80	Eldrege (R)	<1	-	3.5	Minimum RWC impact on CO	Sanborn et al,1980
	9 homes	Indoor (R)	<1	-	1.9		
Albuquerque, NM	12/28/82	Zuni Park (R)	2.0	-	-	Daily average values RWC impact not quantified	Zak et al, 1984
Missoula, MT	1982-84	Boyd Park (C)		13.3	16.5	CO maximum correlated with RWC activities	Carlson, 1984
Portland, OR	1982-84			10.4			Tombleso et al, 1983
Juneau, AK	1/20-3/14, 1983	1 (R,C)	1.2	4.0		About 50% of CO was believed to be RWC related	Chapple, 1983
		2 (C)	2.3	5.5			
		3 (R)	0.8	2.0			
		4 (C)	2.1	4.5			
		5 (R)	0.9	2.0			
		6 (R)	1.0	3.0			
		7 (R,C)	2.7	6.5			
		8 (R)	1.8	5.5			
		9 (B)	0.5	1.5			

ABBREVIATIONS:

RWC = Residential Wood Combustion
R = Residential Site
C = Commercial Site
B = Background Site
avg. = Average
max. = Maximum
CO = Carbon Monoxide

Source: Nero and Associates, Inc., (1984)

TABLE 5.4

Summary of RWC Impact on Fine Mass and Measured Benzo(a) pyrene Levels at Selected Locations

			RWC Impact of Fine Mass μg/m^3			Measure Bezo(a)pyrene ng/m^3		
No.	Location	Study Year	No. of Samples	Average	Maximum	No. of Samples	Average	Maximum
1	Waterbury, VT	81-82	33	19	30	16	0.8[a]	2.4[a]
2	Western, MA	81-82	13	15	25	-	-	-
3	Nashville, TN	83	24	9-20	51	21	2.3[a]	11.4[a]
4	Petersville, AL	81	8	33	65	4	41[c]	110.0[c]
5	Albuquerque, NM	82-83	56	25	59	-	-	-
6	Missoula, MT	83	12	37	48	-	-	-
7	Denver, CO	78	16	6-18	29	-	-	-
8	Telluride, CO	80	13	10-30[a]	59[a]	13	7.4[a]	14.8[a]
9	Reno, NV	83-84	8	13[a]	23[a]	-	-	-
10	Las Vegas, NV	83	4	-	41	-	-	-
11	Boise, ID	80-91	9	85[b]	128[b]	2	1.5	2.3
12	Portland, OR	77-78	32	4-10[a]	50	3	3.2	5.4
13	Medford, OR	79-80	40	9-30[a]	126[d]	2	8.4	8.5
14	Yakima, IWA	80-81	4	50	55	-	-	-
15	Spokane, WA	80-81	15	17-45	68	3	6.1	11.0
16	Seattle, WA	81	9	29	49	3	2.1	4.2
17	Tacoma, WA	81	4	35	44	-	-	-
18	Longview, WA	80-81	4	42	26	-	-	-
19	Anchorage, AK	81-84	8	18[a]	45[a]	-	-	-
20	Juneau, AK	81-82	11	48-93[a]	234[a]	1	-	11.0

ABBREVIATIONS

RWC	-	Residential Wood Combustion
Fine Mass	-	≤ 2.5μm unless otherwise specified
μg/m^3	-	microgram per cubic meter
ng/m^3	-	nanogram per cubic meter
Avg.	-	24-hour average for the study period at one or more sites
Max.	-	24-hour maximum for the study period
PM_{10} or PM_{15}	-	Particulate matter ≤10 or ≤15 μm

FOOTNOTES:

a	-	Analysis of TSP samples
b	-	Analysis of PM_{10} or PM_{15} samples
c	-	Gaseous and particulate benzo(a)pyrene - 4-hour sample
d	-	8-hour or 12-hour maximum
e	-	Annual average
f	-	Samples were taken during heating season, unless indicated otherwise

TABLE 5.5

Summary of RWC Carbon Monoxide Levels for Profiled Locations

Location, State	Samples No.	Samples Date	Monitoring Site & Type	B(a)P Leels in ng/m^3 avg.	B(a)P Leels in ng/m^3 max.	Evidence of RWC Impact, other Organics, Measured, and Comments	Reference
Waterbury, VT	16	1/29/82-3/11/82	Eldredge (R)	0.8	2.4	Many organics measured	Sexten et al, 1984
NAshville, TN	21	1/24-3/31/83	Metro. Autho. (C)	2.3	11.4	No other orgnaics measured	Imhoff et al, 1984
	4		E. Health Ctr. (R)	0.7	1.6		
	1		Background (B)	1.5	-		
	9		McCann Sch. (R)	1.8	3.6		
Petersville, AL	2	2/81	Background (B)	21.0	34.0	Many other orgnaics measured	Imhoff, 1982
Telluride, CO	13	1/80	1 (B)	1.3	3.4		Murphy et al., 1982
			2 (C)	7.4	14.8		
			3 (R)	2.4	7.4		
			4 (C)	-	-		
Boise, ID	2	12/80-1/81	Fairview & Liberty (C)	1.5	2.3	High RWC impact	U.S. EPA, 1984[a]
Portland, OR	3	1-3/81	Marcus Wh.Sc (R)	3.2	5.4	High RWC impact	U.S. EPA, 1984[a]
Medford, OR	2	12/80-1/81	Courthouse (C)	8.4	8.5	High RWC impact	U.S. EPA, 1984[a]
Spokane, IWA	3	2-3/81	Country Home (R)	6.1	11.0	High RWC impact	U.S. EPA, 1984[a]
Juneau, AK	1	11/19/82	Floyd Dryden (R)	-	11.0	All other priority pollutants were below detection	Cooper and Frazier, 1984

ABBREVIATIONS:
B(a)P = Benzo(a)pyrene
R = Residential site
B = Background site
C = Commerical site
Avg. = Average
Max. = Maximum

FOOTNOTES:
a = Profile number in the text

Source: Nero and Associates, Inc. (1984)

The methods for source testing, ambient sampling and chemical analysis were developed as part of the Raleigh, N.C. study (Lewtas, and Cupitt, 1987). The sampling techniques used included: dichotomous and fractionated high-volume sampling with XAD-2 resin backup for semi-volatile organic species, annular denuder sampling for SO_2, NO_3^-, $SO_4^=$, HNO_2, HNO_3, chemiluminescent analyzers for NO, NO_2, and NO_x and a CO monitor. Meteorological parameters also were monitored to enable comprehensive data analysis.

Chemical analysis was performed for elemental and ionic characterization of the fine (aerosol) fraction, Carbon-14 analysis, aldehydes and VOCs.

Results of the studies to date were reported by Highsmith, Zweidlinger and Merrill, 1988. Findings of these studies showed that fine particulate loadings in the evening and night-time were more than twice the values acquired in the daytime samples. Analysis of the fine particulate fraction (0-2.5 µm) established that, on average, approximately 60% of the night-time samples were extractable organic compounds. Although potassium and carbon-14 tracer analyses were performed, the ratios of fine fraction total mass to the tracer compounds were not shown to differ between daytime and nighttime samples beyond the inherent error of estimate.

The study conducted in Boise, ID was recently concluded. Preliminary results were reported (Stevens et al., 1988; Lewis, Dzubay et al., 1988), and survey results were outlined by Cupitt and FitzSimons (1988). The source testing of typical stoves and wood types was reported by McCrillis and Burnet (1988).

Bioassay and human exposure assessments, also were included in the experimental design. The tracer constituents used to distinguish woodsmoke were lead, C-14 and potassium (Lewis, 1988).

Study of Six Northwestern U.S. Cities

Carbon monoxide levels were studied in six northwestern U.S. cities, namely; Boise, Idaho; Eugene, Oregon; Libby, Montana; Missoula, Montana; Portland, Oregon; and Yakima, Washington. The results of the study were presented at the APCA Toxics Conference, 1988, (Hornick, Simons and Snow, 1988). It was found that CO levels were highest on holidays, evenings, next highest on weekend evenings, and lowest on weekday daytime samples. Some discrepancies existed in the light scattering (b-scattering) ratios, and it was suggested that larger particles from other sources caused interferences.

Klamath Falls, Oregon RWC Studies

Winter survey monitoring conducted in Klamath Falls, Oregon in January, 1984 detected PM_{10} concentrations as high as 300 $\mu g/m^3$, 24 hour average. Since 1984, 24-hour winter worst case PM_{10} concentrations as high as 692 $\mu g/m^3$ have been measured with 3 hour average nighttime concentrations as high as 900 $\mu g/m^3$. Atmospheric lapse rate measurements have shown intense, very shallow inversions that under worst conditions were 12 to 15 meters above ground level. Wood use surveys indicated that the average wood heating household burns 4.2 cords of wood each winter and that 60% of the residents use woodstoves as their principal source of heat. Integrating nephelometer measurements of the spatial distribution of the woodsmoke showed a pattern that is consistent with residential home density and areas of low topography. Emission inventory studies showed that worst case winter day PM_{10} emissions were 70% woodsmoke. Chemical Mass Balance source apportionment results for poor air quality winter days agreed with the inventory and apportioned the balance of the PM_{10} mass to soil dust from winter road sanding (25%), wood products industry emissions (2%) and secondary aerosols. Secondary nitrate levels reached 40 $\mu g/m^3$, (3 hour average) during winter evenings. A health effect study designed to measure lung function effects on 3rd to 6th grade children is being conducted in the airshed this winter (1989-90).

Study of Fireplaces In Las Vegas, Nevada

High nighttime fine particulate and CO levels were attributed to wood combustion in fireplaces in Las Vegas, Nevada. The Clark County Health District conducted 12-hour sampling of fine particulates ($\geq 3\mu m$), CO, C-14, methylchoride and organic compounds (via canister sampling). The sampling location was approximately 2.5 miles from the main strip in Las Vegas. Although this site was classified as residential, caution to the conclusions regarding the impact of fireplaces should be advised. Unlike other North American cities, activity levels in Las Vegas do not decrease in evening and nighttime hours. Winters are particularly moderate (average winter day-time temperatures of 60°F) and the cost of fuel wood is relatively expensive (~$150/cord). Hence, the Las Vegas study is not generally representative of a wood-burning community.

Woodburning in Mio, Michigan

High-volume sampling was conducted at five stations in Mio, Michigan. The study was performed by the Michigan Department of Natural Resources, during the period February 4-17, 1984. TSP, BAP, IP, CO and associated meteorological parameters (wind speed and direction, temperature and humidity) were monitored. The monitoring activities were accompanied by door to door surveys, examining woodburning practices. As in other woodburning studies, it was surmised that RWC contributed significantly to haze; CO and fine particulate levels (Engel, 1985).

The limited time period of the study and the lack of source apportionment analyses limit the interpretation and scope of the results.

Lake Tahoe Visibility Study

Pitchford and Allison (1984) examined airborne particulate matter and visibility in the Lake Tahoe basin. Two size fractions were sampled and visibility was determined by a variety of methods. Particulate matter also was analyzed for elements with atomic number greater than Na. A linear model was used to attribute source contributions. The authors concluded that RWC accounted for 60% of the visibility impact, but cautioned the limitations of the short study duration and the use of a linear model rather than actual monitoring of tracer compounds with source characterizations.

Particulate Emissions from RWC in Greenville, N.C.

This study of RWC impact (Lao, 1983), focused on the toluene extractable compounds sampled at two sites using high volume samplers. No identification of compounds was performed. No source apportionment analysis was included; hence, conclusions regarding wood stove contributions were not substantiated.

RWC Study In Telluride, Colorado

The study conducted by Murphy et al., 1984 concluded that TSP and BAP levels varied seasonally, corresponding with woodburning practices. Sampling was conducted using high-volume samplers with glass fibre filters. No special backup cartridge was employed under the assumption that all of the BAP was adsorbed to the surface of particulate matter. Analysis for BAP was performed using a HLPC instrument equipped with a multiwave length absorbance detector. The actual study duration was 13 consecutive days in January. Source resolution was attempted using meteorological factors (upwind/downwind). Assumptions regarding the contribution of RWC and TSP were generally not conclusive.

CANADIAN STUDIES

RWC Impact Studies In Canada

Limited monitoring of the ambient air quality RWC impacts have been conducted in Canada. Canadian initiatives to address the impact of residential wood combustion have been undertaken in the Atlantic provinces, at urban centres in Ontario and in the Northwest Territories. The ambient PAH and BaP concentrations measured are reported in Table 5.6. Areas conducive to poor dispersion conditions (e.g., Whitehorse) experienced the highest BaP and other PAH concentrations. A brief outline of the monitoring studies is provided in the following paragraphs.

Impact Studies In Atlantic Canada

Air quality studies were conducted by the Environmental Protection Service in two locations in Nova Scotia and in one location in New Brunswick in conjunction with the N.S. and N.B. Ministries of the Environment. The work was conducted in the heating season 1984/85. The locations sampled were:

(i) Truro area, N.S.; population: 12,552; 3 sites
(ii) Lower Sacksville; N.S., population: 33,581; 4 sites
(iii) Fredericton, N.B.; population: 47,000; 3 sites

TABLE 5.6

Summary of BaP and PAH Data from Canadian RWC Impact Studies and Other Urban Area

Location	BaP (ng/m^3)		PAH (ng/m^3)	
	Average	Range	Average	Range
County Jail, Sydney (Atwell, 1984)	1.74	0.02-36.42	31.6	0.36-622.4
Frederick St., Sydney (Atwell, 1984)	3.74	0.06-21.14	36.56	0.69-201.56
Control Site, Sydney (Atwell 1984)	0.23	ND-1.98	3.48	0.09- 23.70
Hamilton, Ont. (Katz 1979)	2.30	1.40-3.50	18.67	9.85-32.15
Toronto, Ont. (Katz 1979)	1.06	0.72-1.67	11.05	7.86-17.36
Riverdale #1, Whitehorse (McCandless, 1984)	9.8	1.2-30.6	364.2	31.6-1950
Riverdale #1, Whitehorse (McCandless, 1984)	15.8	6.7-50.6	729.8	181-2530
Riverdale #3, Whitehorse (McCandless, 1984)	15.3	0.96-44.7	700.9	11.8-2242

The Nova Scotia sites monitored TSP (by hivol) and one PAH measurement at each location. TSP, PAH and nephelometer measurements were conducted in Fredericton, New Brunswick. The data have been compiled in a preliminary report; however in discussion with the author, further data validation is considered necessary before the values are released.

Whitehorse RWC Impact Study

The most extensive measurements of RWC impacts in Canada have been made in Whitehorse (Senes, 1983; McCandless, 1982, 1984; Davis et al. 1987), where such impacts have been described as severe (McCandless, 1984). The extensive use of wood as fuel for residential heating and the bowl shaped topography exacerbate the RWC impacts on air quality in Whitehorse. Measured and predicted TSP levels in the residential area (Riverdale) of Whitehorse during the heating season were deemed likely to exceed the Canadian National Air Quality Objective for the 24 h average TSP level of 120 $\mu g\ m^{-3}$ once in every three days. PAH measurements in Whitehorse were highly correlated with TSP levels. The Chemical Mass Balance method applied on the basis of inorganic source profiles and ambient data indicated that about 90% of the TSP loading was due to RWC (McCandless, 1984). Recently, limited ambient as well as simultaneous indoor measurements have been made in Whitehorse (Davis, 1987; Otson and Goddard 1988).

Carbon monoxide levels were nonexclusively associated with RWC activity since measured CO levels were lower in Riverdale than in the downtown area of Whitehorse. CO levels in Riverdale at night were higher than in the downtown area (McCandless, 1984).

Although RWC impacts have been suggested for other areas of Canada, monitoring data have been collected to characterize ambient PAH levels associated with urban or industrial activity. The ambient PAH data derived from studies such as the monitoring in Toronto, Montreal or Vancouver (Dann, 1988), or in Sydney (EPS, 1984) with these studies are excluded from this summary.

5.2 SUMMARY

Many studies have investigated the impacts of RWC on various airsheds in woodburning communities in the U.S. Source apportionment was conducted in several of these studies. While sampling and analytical techniques are well defined, the largest obstacle to evaluating the effect of RWC on local air quality is the unique apportioning of pollutants measured to RWC activities.

Monitoring of RWC impacts on air quality in Canada have been limited and only one ambient source apportionment study related to RWC has been reported.

6 DATA ANALYSIS TECHNIQUES FOR RWC SOURCE APPORTIONMENT AND AIR QUALITY IMPACT ANALYSIS 6-1

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6 DATA ANALYSIS TECHNIQUES FOR RWC SOURCE APPORTIONMENT AND AIR QUALITY IMPACT ANALYSIS

6.1 INTRODUCTION

Source measurements quantify the emissions to ambient air, whereas ambient sampling produces a collective measurement of many effects. The relationship between emissions and air quality is therefore complex and the challenge of current woodsmoke studies is to distinguish the contribution of woodsmoke emissions from other sources. The physical and chemical characteristics of emissions caused by most combustion processes are so similar that this grouping of sources is extremely difficult to separate. The overlapping nature of temporal and spatial distributions of sources, such as residential wood combustion and automotive emissions, also augment these difficulties.

A variety of methods, and combinations of such, have been used to resolve woodsmoke emissions from other sources. The objective of assessing relative source contributions can be categorized into two domains:

i) statistical methods; and
ii) direct identification methods.

Statistical methods have evolved from hypothesis testing, multivariate regression techniques, factor analysis and matrix reductions. Mathematical models also have been developed to simulate indoor and outdoor dispersion of source emissions. Specifically, the methods of source apportionment that are statistical in nature comprise:

- hypothesis testing (e.g., upwind/downwind comparisons);

- regression techniques (least-squares, linear, curvilinear and multivariate);

- factor analysis (an extension of the multivariate regression techniques employing matrix manipulations);

- chemical (or elemental) mass balance (simultaneous solving of linear mass balance equations); and

- mathematical simulation equations (dispersion modelling).

Statistical methods have evolved from single variable regression to more sophisticated methods such as CMB analysis and mathematical simulation (modelling) for numerous environmental concerns. Whether the source is simple or complex; if the emissions from a process or reaction are easily identified with accuracy and reproducibility, these sources can be resolved with an average characterization of the source. The variabilities (Section 3) that impinge upon wood burning emissions characterizations, represent new challenges in source apportionment techniques.

The direct methods of RWC emissions identification, probe for direct evidence of the source's influence on ambient samples. Two common methods of identification are:

- morphological investigation; and
- source tracing via tracer compound(s) or other source characteristic(s).

Morphological investigation involves the identification of particles collected on the sampling medium (e.g., filter surface) using optical or electron microscopy. The physical appearance of particles is used to distinguish its general origin and possible composition (e.g., flyash particles appear smooth and round with distinct grey colour).

In contrast, source tracing methods focus on the internal and inherent characteristics of emissions. Characteristics that uniquely define emissions from a source are used as indicators or tracers. With knowledge of the relationship between the total emissions and the tracer characteristic, the source contribution is directly discernible.

These methods of source apportionment are discussed in the following subsections.

6.2 STATISTICAL METHODS

The standard statistical methods of determining the existence and the significance of an effect have been adapted for environmental applications. The statistical tools that have commonly been used to assess and quantify effects generally have employed linear regression techniques (Lewis et al., 1988) and more sophisticated factor analysis (Koutrakis and Spengler, 1986; Daisey and Hopke, 1984), chemical mass balance (Watson et al., 1988), mathematical simulation (modelling) and estimation (Imhoff, 1985).

Early studies attempted to isolate RWC by upwind/downwind studies, with little success. Examining other possible unique characteristics involved size fractionation; however, the similarity between RWC and other combustion sources rendered the distinction between source types as inconclusive.

Multivariate Linear Regression Analysis

The basic least-squares regression technique is extended to several dimensions to explain the behaviour of a dependent variable in multivariate linear regression analysis. The independent variable is usually the mass or PM_{10} mass. The desired solution is an empirical equation of the form:

$$y = A\, x_1 + Bx_2 + Cx_3 + \ldots\ldots\ldots + \text{Constant}$$

A series of iterations fit the independent variables and an assessment of the reduction in variability is made. This type of empirical solution is effective as a predictive tool if the important (primary) variables are included and well defined. The secondary or lesser effects reduce the variability further, and in the case of complex systems describe fine-structures and anomalies.

The application of multivariate linear regression (MVLR) to the environmental sciences has been multi-facetted because of the predictive qualities and the ease with which a statistical confidence may be quantified. The relationship between the variables can be summarized by a simple equation with a quantifiable level of confidence.

MVLR has been used to explain and predict ambient air quality as a function of past observations (measured concentrations). In the investigation of RWC, MVLR has attributed pollutants such as CO, aerosols, PAHs, etc. to RWC activity. While successes have included the further examination of significant factors (e.g., potassium as a tracer compound) the complex nature of the combustion process and the numerous influencing factors have limited the success of a linear solution. However, the basic concept of MVLR is employed in statistical analyses of higher sophistication (Factor-Analysis, CMB). The effectiveness of the method is greatly extended when a unique, direct relationship can be established and also is independent of other physical and chemical variables. MVLR is an effective tool for apportioning measured RWC effects provided that unique tracers can be defined. A discussion of tracer methods is provided in the latter part of this section.

Factor Analysis

Further investigation has focused on chemical characteristics. Factor analysis examines least squares regression coefficients to determine the relative importance of various factors (chemical characteristics) influencing a variable of interest (sample concentrations). The method employs a matrix of correlation coefficients to distinguish underlying variable interrelationships. In essence, factor analysis is a multivariate form of the commonly used correlation coefficient. The concentration data (represented in Equation 4.1 as Z_{ij} for sample i and species j) are assumed to be linearly related to a number (k) of underlying causal factors and a unique factor U_i, and are represented as the sum of the product of a set of factor loadings (a_{ik}) and factor scores (f_{kj}).

$$Z_{ij} = \Sigma \ (a_{ik} \ f_{kj}) + U_i \tag{4.1}$$

The factor loadings represent the correlation coefficients between the factors and the original variables, while the factor scores indicate the relative importance of each factor to each sample.

To perform factor analysis, the data are first standardized and a correlation matrix with all variables is calculated. Variables which are not associated to other variables can be identified from the matrix and the associated statistics. Factors are then extracted and the number of factors that are suitable for inclusion in the subsequent analysis is determined.

The ultimate result of factor analysis is an empirical (linear) function minimizing the independent variables necessary to describe the dependent variables. Reduction of independent variables to describe an observed effect is of particular interest in situations where many factors are explored simultaneously.

This statistical tool may be used without an *a priori* knowledge of the relative importance of factors to obtain qualitative results. Such analyses are used as an exploratory technique to eliminate insignificant factors or collinear factors. The relative importance of factors cannot be determined quantitatively with confidence in this preliminary extraction of factors.

When the number of factors have been reduced to a workable size, it is possible to obtain an empirical solution by successive rotations of the correlation matrix. The order of matrix rotations and manipulations become important in the formulation of a statistical solution. To produce the most representative empirical solution, the order of predominant factors (from most important to least) is vital.

In environmental applications, factor analysis has been used successfully as an exploratory tool to identify factors that may be of interest. The *a priori* knowledge of order required to derive an empirical solution is often not at hand in novel experimental studies, and the error in the empirical solutions defined, have been evaluated as significant (Henry, 1985).

Aside from the elemental compositions commonly used, elemental ratios associated with the suspected sources; such as Pb/Br for vehicles and K/Cl for RWC also have been explored. The limitations of this method are interferences with other sources (e.g., soil, industrial processes, etc.) and the inherent uncertainties of stepwise factor analysis that have been cautioned by investigators (Henry, 1985). It is important to resolve the factors with an order of importance that roughly places largest factors within the first few iterations.

Lewis et al., (1986), (Denver Winter Haze Studies) performed a more sophisticated form of factor analysis using factor groupings (or clusters) for the elemental analysis and a limited set of gaseous constituents. Both coarse and fine particulate compositions were analyzed separately using this particular variation of factor analysis. The preliminary examination of elemental factors eliminated values with an r-value less than 0.80. Aerosol samples were analyzed for NH_4^+, NO_3^- and $SO_4^=$ and gaseous sampling was conducted for NO_x and CO. All components were compared for relative strength of factors, and erroneous factors were eliminated in a stepwise manner. Intercomparison of factor analyses for fine and coarse aerosol and gaseous fractions consistently resulted in the same order of source importance.

The elemental groupings chosen were different for the coarse and fine fraction, as expected, from different sources. For the two size fractions, the resultant empirical equation was:

Coarse: $M_c = 1870 + (30.3 \pm 1.5)\ [Fe] + (3.12 \pm 0.75)\ [Cl]$

$(n = 34,\ r^2 = 0.96)\ (ng/m^3)$

Fine: $M_f = 1080 + 1.29\ [NO_3] + 5.00\ [Si] + (22.7 \pm 2.9)\ [Pb] +$

$(7.81 \pm 1.08)\ [S] + (68.4 \pm 19.3)\ [K^1]$

$(n = 36,\ r2 = 0.90)$

$[K^1] = [K] - (0.14 \pm .02)\ [Si]$

The source profiles defined for apportionment were soil, motor vehicles, woodsmoke and sulphate, for the fine fraction; and soil and street salt for the coarse fraction.

The weakness in an approach that uses so few components to characterize sources, is establishing uniqueness conclusively. The statistics for goodness of fit (e.g., r^2 coefficient) will be artificially high, since the degrees of freedom are so few. In practical terms, it cannot be concluded that all sources with collinear profiles have been resolved based on factor apportionment.

Chemical Mass Balance

The roots of chemical mass balance exist in the multivariate matrix solution of the sample (dependent variable) using chemical characterizations of both sample and possible sources. The goal of CMB analysis is to attribute the chemical composition to a superposition of source fingerprints. In simplistic terms, CMB involves solving the simultaneous equations relating total mass and chemical composition of sources and sample. The equations to be solved are of the form:

$$C_i \quad = \quad m_1 \, x_{1i} \quad + \quad m_2 \, x_{2i} \quad + \quad \ldots \quad m_n \, x_{ni}$$

where:

C_i = sample concentration of compound i
x_{ni} = source concentration of compound i for source n

CMB uses unique ratios of chemical constituents for each source type to account for the chemical composition of the collected sample. The goodness of fit is assessed through linear regression at each point of the iteration, hence the order of iteration is not dependent on the rank of source importance.

In practical terms, this enables statistical source apportionment that does not require a predetermined order of sources. The solutions provided by CMB analysis are source specific rather than compound specific, reducing the possibility of subsequent misinterpretation.

The limitations of CMB are the following:

i) collinear source profiles cannot be resolved;

ii) accurate source characterizations and sample analyses are imperative;

iii) the components of the chemical characterizations (i.e. profiles) must be greater than the number of sources to be apportioned;

iv) source profiles of all significant sources must be present in the analysis; and

v) source profiles must include constituents common to those analyzed in the sample.

The application of CMB to resolve individual sources was enabled by advancements in both sampling and analysis. Originally, CMB used elemental data obtained by XRF analysis (Gordon, 1980) to apportion material collected on dichotomous samples (fine and coarse) to soil, coal, limestone, oil, refuse, motor vehicles and sea salt sources. Nine marker elements along with ten floating elements were used with promising success. Further refinements to the chemical mass balance models were made in successive efforts (Watson and Cooper et al., 1989).

A compilation of standard source profiles has been continually updated and expanded as a U.S. EPA activity (Core, Shah and Cooper, 1984). These profiles are available in hard copy and electronic format. However, the profiles generally characterize particulate fractions (fine and coarse) and are a composite (average value) of source tests conducted throughout the United States. Source profiles, including gaseous constituents for residential wood combustion, have received much current interest and have enabled new work to apportion the gaseous compounds, many of which are suspected carcinogens. As discussed as part of Section 3 in the overview of source characterization studies, the currently available source profiles include a fairly comprehensive list of organic compounds in particulate and also in the gaseous phase. However, as was noted by Rau and Huntzicker, (1987), actual source profiles significantly enhance CMB analysis and provide more accurate and realistic source apportionment.

Since the conception of using trace organic constituents and volatile organic components in profiles, the chemical mass balance process has reached a transition point. The concept of simultaneous equations relating concentrations of elements and compounds to total mass can be extended to include the gaseous components by using a surrogate normalizing factor (personal communication, Watson, 1989) that is common to source and sample composition, or determining a total mass based on a calculated value (Shah, 1989). While this novel method of receptor modelling is very promising for the quantification of RWC sources, new considerations arise, such as:

i) the reactivity and transformation of compounds from source to receptor;

ii) the variability of source patterns due to influencing physical and chemical factors;

iii) the collinearity of sources;

iv) the representativeness of the surrogate for total mass or inherent error of the total mass estimate; and

v) the lack of compatible (common compounds) source profiles.

To summarize the current status of CMB receptor modelling, the CMB method of source apportionment has been proven effective for the apportionment of particulate samples with many different source types. The different factors affecting RWC emissions and the problem of obtaining representative source profiles due to the variability and complexity of the source matrix, necessitate source specific profiles. Some efforts have been made to produce source profiles of RWC under more specific conditions, and to include polynuclear organic material (POM) to distinguish emissions of wood combustion sources from other combustion sources (Wood and Hardy, 1988). At present, elemental CMB analysis has not determined RWC sources conclusively without the combination of other methods of source identification (morphological identification or tracer compounds). The inclusion of organic compounds has been pioneered with success (Shaw, 1988; Watson, 1989; and Otson et al., 1989).

The nature of RWC emissions has been examined in much detail for various conditions (Ward and Hardy 1989) and has substantiated the need for specific source profiles and extension of the compound list to include suitably stable organic compounds.

6.3 DIRECT METHODS OF SOURCE APPORTIONMENT

Source Specific Tracer Compounds

Tracer compounds enhance the resolution of a specific source in source apportionment methods. With the aid of a unique tracer compound that can be determined analytically, the confidence limits of receptor modelling can be determined within a few percent. Tracer compounds have been used in conjunction with:

- multivariate regression analysis;
- factor analysis; and
- CMB.

The concept of a tracer is based on a unique chemical or physical characteristic of the source that is not present in other suspected sources. The total contribution of a source type to the total sample (and hence the ambient impact) can be quantified on a relative basis if a tracer quantity can be defined in both the source measurement and the sample measurement. Characteristics that have been used successfully for other source types include:

- radioactive isotopes;

- trace elements;

- elemental ratios;

- isomers and polarity of molecules caused by formation mechanisms; and

- trace organic compounds.

Attempts to obtain a unique tracer for emissions from residential wood combustion have achieved varying degrees of success. Tracers of RWC that have been investigated are:

- C-14 tracer;
- potassium;
- methyl chloride; and
- levoglucosan.

Methyl chloride (CH_3Cl) has been investigated as a possible tracer of RWC. The choice of CH_3Cl was based on the relative stability of the compound in the atmosphere (> 1 year) and its presence in emissions from RWC. The shortcoming of using CH_3Cl as a tracer is the existence of this compound in other natural and anthropogenic sources. Oceans and microbial processes are natural sources of CH_3Cl; and these may be distinguished with confidence. However, interferences from other combustion sources (vehicular and fossil fuel combustion) are a significant handicap (Khalil and Rasmussen, 1988). The general mass balance equations used in discerning RWC emissions using CH_3Cl as a tracer, are:

$$CH_3Cl = CH_3Cl\ (background) + CH_3Cl\ (RWC)$$

$$H_2 = H_2\ (background) = H_2\ (RWC) + H_2\ (automotive)$$

This method has been used to attribute residential wood combustion in the home and yard (Edgerton et al., 1984). However, error bounds between the residential site and the background site overlapped in crucial heating periods.

A natural tracer of woodsmoke is produced during the formation of wood fuel. Carbon-14 is produced during photosynthesis throughout the living cycle of vegetative matter. The production of C-14 ceases as photosynthesis ceases. In materials (organic and inorganic) that do not produce C-14 actively, this isotope of carbon exists in very small quantities. It is this difference in the formation process of wood fuel and fossil fuels (petroleum, oil, coal) that has been used to resolve the combustion sources (Currie, Klouda and Gerlach, 1981). The principle of extrapolation is used to determine the wood combustion contribution to total carbon in the sample. The method does assume a 14-C to total C ratio; and thus assumes an average tree age and wood type.

A comparison of results using the C-14 method and multiple linear regression (with $[C_i] \alpha [K_i']$ and $[Pb_i]$) has demonstrated that estimates of total Carbon were within the error bounds for the two methods (Lewis, Baumgardner, and Stevens, 1988). Typical errors of estimated total carbon are within 6 to 10 percent.

Levoglucosan is a sugar characteristically produced in trees. In pyrolysis under normal woodstove conditions, this compound is present in the particulate emissions, due to incomplete combustion. Being of natural origin, lavoglucosan is not present in anthropogenic sources or background sources such as soil. This property has sparked interest for levoglucosan as a tracer method (Hornig, et al., 1983). The disadvantage of using levoglucosan as a tracer is that its possible transformation during pyrolysis would generally underestimate RWC contributions in source apportionment.

Historically, the seasonal variation of potassium levels in wood burning communities inspired investigations of potassium as an indicator of residential wood combustion. It was noted that ambient concentrations of potassium in the fine particulate fraction rarely exceeded 0.1 $\mu g/m^3$ in winter months corresponded with wood burning activities (Stevens, 1985). The advantages of using potassium (K) as a tracer is the ease of analysis (XRF) and stability of potassium throughout the pyrolysis process. Interferences arise in the natural sources of potassium; in particular, reentrainment of local soil. In recent refinements to the potassium tracer method (Calloway, Li, Buchanan and Stevens, 1989), a soil correction factor based on a K/Fe ratio in local soil has been employed. It was demonstrated that potassium from woodsmoke is water soluble and potassium from local soil is virtually insoluble in water. This characteristic has been used to limit the need for local soil analysis within an experimental error of approximately 40% (95% confidence level).

Morphological Analysis

Morphological analysis involves the direct determination of particle origin and general composition by visual identification. Optical and electron microscopy is a useful tool in the inspection of particulate samples. Size, shape and surface characteristics generally can determine the particle type. A statistical count over an appropriate area can apportion the mass of the sample to various source types. This method of source apportionment does not resolve the combustion sources with confidence, but has been used effectively to distinguish combustion emissions from natural pollen, minerals, sea salt, etc. (Dzubay and Mamane, 1988). When used in combination with other source apportionment methods, morphological analysis has helped to resolve sources with increased confidence.

7 CONCLUSIONS AND RECOMMENDATIONS 7-1

7.1 CONCLUSIONS 7-1

7.2 RECOMMENDATIONS 7-3

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The conclusions of the literature review will be directed at addressing the following questions:

i) Is there the potential for significant air quality impacts due to residential wood combustion in Ontario?
ii) If there is, what is the magnitude of the impacts?
iii) If necessary, how can the impacts be alleviated?

This review has cited several areas in the U.S. and Canada in which there have been adverse air quality impacts. The climate of most areas is similar to that in Ontario - in the sense of winter temperatures; but several areas are located in mountainous areas and with orographic features (valleys, bowl shaped topography) that are conducive to poor dispersion conditions. The potential for adverse RWC air quality impacts are largely dependent on the extent of RWC use. In areas where there is heavy use of residential wood fuel, the potential will therefore exist. The only evidence for such impacts in Ontario included in this study, is the complaint log information which are attributed to residential wood use. The complaint information provided in this report is clearly an underestimate of the situation since the information is known to be incomplete for some areas. Other potential indicators of the degree of impacts could be derived from historical ambient air quality data in the areas in which there have been complaints, and the first hand knowledge of the region. On the basis of the complaint information and the experience in other areas of the U.S., it is clear that the potential for significant adverse RWC air quality impacts exists in Ontario. The familiarity of OME personnel with each region will be invaluable in the selection of potential locations.

In order to assess the potential impacts, the obvious action is to conduct specific monitoring activities to assess the extent of the impacts. Methods for conducting such assessments, and factors that should be addressed in such a study have been reviewed. These factors specify the scope of the required study. In particular, the assessment could involve ambient air monitoring and analysis, source characterization and data analysis, such as receptor modelling (Chemical Mass Balance (CMB)).

Historically, monitoring has been mainly for inorganic species (elemental analysis, ions, various types of carbon analyses) in cases where source apportionment is required. In other cases, monitoring for organic compounds, especially PAH and volatile organic compounds (VOC) has been conducted. Source apportionment based on organic species has received relatively little attention - due to the lack of suitable source characterization information. This deficiency has been addressed recently, but as indicated by the literature reviewed, the physical variables of RWC affect emissions significantly. Therefore, it is important to obtain site-specific source characterization information. The most recently available source characterization information applies to residential woodstoves manufactured in the U.S. and also to specific tree species. Since no information on emissions specific to Canadian fuel types and woodstove types exists, the necessity for further study is clearly evident. Approximately 90% of all woodstoves used in Ontario are of local manufacture and fuel wood types commonly burned are very different from those for which there is source characterization information. It is therefore stressed that Ontario-specific source information be obtained for reliable assessment of RWC air quality impacts in Ontario.

Given the need for assessment of existing RWC impacts, recommendations for the conduct of such assessments are provided. The methods recommended are based on the currently best available sampling and analytical methods and techniques for data analysis. Details of the methods are provided in the following section.

The review of regulatory approaches provides a comprehensive range of approaches in various jurisdictions apply in dealing with the control and abatement of RWC air quality impacts. It is premature to suggest possible approaches that may be suitable for implementation in Ontario.

7.2 RECOMMENDATIONS

The potential for increased RWC air quality impacts in Ontario is anticipated to increase with the number of woodstoves. It is recommended that an assessment of the RWC impacts be conducted by a monitoring and assessment program to be followed, as necessary, by recommendations regarding possible control measures.

A strategy for these efforts is outlined below.

a) identification of areas with RWC emissions impact

b) ambient monitoring for source apportionment and RWC impact assessment

c) source characterization measurements

d) evaluation and assessment of RWC air quality impacts

Identification of Areas With Potential RWC Emissions Air Quality Impacts

The first step in the investigation of RWC in Ontario is to identify areas of possible RWC air quality impacts and to select areas for intensive monitoring studies. RWC emissions in Ontario have not been characterized or quantified to date. Data on the extent of wood usage, the number and types of woodstoves, and operating practices, are required to assist in identifying suitable communities. Ideally, a community survey of wood use should be conducted at the same time as monitoring. Such surveys should be conducted in a selected number of communities, for example, those with anticipated high numbers of woodstoves or with a large number of complaints regarding RWC air quality impacts. In addition, ambient air quality data from the OME (as well as from the National Air Pollution Survey (NAPS) network) will provide some historical information that should be analyzed in conjunction with the wood use survey and first hand knowledge of each region. A small number of communities (say 6 to 8) should be selected for such a survey in order to identify potential sites (1-3) at which intensive monitoring would be conducted. Assistance of OME personnel familiar with their respective regions in the determination of potential RWC impacted areas will greatly enhance selection of monitoirng locations.

Ambient Monitoring

Monitoring objectives will determine the nature and extent of sampling and analysis that is conducted. The suggested approach is to establish the contribution of RWC emissions to ambient air quality in up to 3 communities in Ontario. Woodstoves operations data should be obtained in a survey conducted concurrent with the monitoring program (using questionnaires). The monitoring strategy should include specification of the target compounds, and the sampling program (duration, location, sampling method, analytical methods, QA/QC requirements) for an intensive survey of limited duration.

Monitoring for the intensive survey should include sampling to collect size segregated (inhalable fraction) particulate matter for mass, carbon, elemental and organics analyses, and vapour phase sample collection for organics analyses. Suitable source profiles including soil samples (for use in the potassium tracer technique), should be taken at the same time. For size selective sampling, standard equipment for inhalable particulate sampling with a backup sorbent for semi-volatile species will be required. Meteorological parameters would be required also and would be sought from local airport stations. The location of samplers is critical in view of the low stack heights in residences and the potential for complicated influences of buildings. Suitable analytical methods include x-ray fluorescence (XRF) for elemental analysis (especially K, for tracer analysis), and GC/MS for VOC and PAH. The customary QA/QC component for any sampling program should be included as an integral part of the study.

The potassium analysis will allow application of the potassium tracer technique to samples collected during woodburning season. This information would be analysed in conjunction with other air quality data and wood use information. If overlap between the Toxics Deposition Monitoring Network and the woodstove study exists in the selected woodburning communities, the information on PAH and inorganic species would be used to enhance ambient monitoring data and could be included in further CMB determination.

Evaluation and Assessment of RWC Air Quality Impacts

The data analysis and assessment should be highlighted by chemical mass balance (CMB) with prior application of factor analysis to assist in the identification of potential sources (by assuming that factors could be associated with sources). The CMB should be applied for both inorganic and organic fitting compounds.

The assessment of the contribution of RWC to ambient air quality together with reliable information on usage of wood as residential fuel in the communities will provide indications of the extent of the RWC air quality impacts. Information on wood usage in other communities together with appropriate extrapolative techniques e.g., dispersion modelling or simple linear extrapolation, will provide sufficient information to determine the need for control measures.

The data to be collected in the proposed air monitoring program are summarized below:

- high-volume sampling with size selective inlet and PUF backup cartridge at 3 locations for a duration of at least one week (7 days)
- woodstove/burning practices survey via questionnaires
- soil sampling
- quality control/quality assurance
- analysis of elemental and organic constituents (XRF and GC/MS; respectively)
- data analysis including application of potassium tracer techniques
- report to document study and present results/conclusions.

The estimated cost of an ambient monitoring program has been provided in several ways. Firstly, the minimum of 2 samples at each location has been costed using CSC personnel. Savings in both labour and non-labour costs by substituting OME field operations have been analyzed. Because meteorological conditions (such as precipitation; both rain and snow) affect the ambient concentrations by scavenging mechanisms and ground cover effects, a larger sample set is desirable (i.e., study duration longer than 1 week). Additional sampling days beyond the minimal 7 days have been costed (including both labour and non-labour breakdown of costs) on a per sampling day basis (Option 2). Again, if OME responsibility for field operations is assumed, the per diem **labour** costs would be saved, as well as the travel expenses. In the event that OME personnel conduct the field sampling, it is advocated that the QA/QC audit be conducted externally by CSC personnel.

Ambient Monitoring Program - CSC Staffed

Labour Costs

Tasks	CSD	MEY	MU	SEB	MP	Word Processing
1. Project Initiation and identification of locations	5	10	-	-	-	-
2. Site selection	10	30	25	-	-	-
3. Woodburning survey via questionnaires	-	10	-	25	-	-
4. Setup and shutdown	-	-	15	15	10	-
5. Operation (1 week, 7 samples at 3 sites) (assuming 1 location in driving distance)	-	5	38	38	20	-
6. QA/QC	-	-	30	-	-	-
7. Data analysis	15	40	-	30	-	-
8. Draft report	15	30	-	-	-	30
9. Final report	10	15	-	-	-	10
Totals	60	140	83	133	30	40
Rates	$115	75	40	55	55	45
	$6,900	10,500	3,300	7,315	1,650	1,800
Labour	$31,465					

Labour Costs using OME staff for setup, operation and shutdown	$23,500
Non Labour Costs	
Sample Analysis (XRF, GC/MS, grav. combined @ $600/sample (27 samples), (9 blanks)	18,000
Soil analysis	1,000
Equipment Rental	1,500
Travel and accommodation	5,500
Consumables (filters, cartridges, gases, etc.)	4,000
Computer costs	2,000
	32,000
Assuming OME equipment and sampling personnel - Non Labour Costs	$ 26,500

OPTION 1

CMB analysis (Optional)	$ 8,500

OPTION 2

for each additional day of sampling at all three sites add:

Analysis: (3 samples, 1 blank)	$ 2,400
Labour: (3 man days)	1,210
Equipment/Consumables:	200
Extra Travel expenses/accommodations	300
	$ 4,110

LABORATORY SOURCE STUDY

The source characterization of woodstoves used in Ontario communities is a critical aspect of any future work in this area. The strong dependence of emissions on stove type, fuel (type of wood), and operating practices are the factors that warrant the acquisition of community-specific source information. The minimum variables that require study with respect to source characterization are:

i) stove type (popularly used woodstove types in Ontario), (approximately 3 types)

ii) wood fuel type (birch, maple, pine)

iii) operating practices.

The purpose of the source study is to define the emissions produced by the combustion of locally available woodfuels in the 3 popular woodstoves manufactured in Ontario. While several sampling methods have been considered, it is proposed to use the U.S. E.P.A. Method 5G with the sampling train illustrated in Appendix B. Cost for the work and required equipment have been assembled. The cost for the three types of woodstoves in popular use is included; and in the event that cooperation can be gained by the manufacturers these savings will be reflected in overall costs.

The tests would commence with a series of sampling train calibrations (flow velocity, temperature, humidity, etc.) then successive tests (3) of the three wood types (birch, maple and pine would be obtained) for the particular stove. Size selective filter cartridges (both teflon and firefired quartz fibre) will sample 2 size fractions:

i) >2.5 µm, and
ii) 2.5 - 10 µm

using two Sierra model 244 dichotomous impactors that are modified to accept 47 mm filters (for sufficient sample size).

The two filter types will enable analysis of both elemental and organic constituents. Chemical composition will be determined using X-ray fluorescence analysis for selected elements, and gas chromatography coupled with mass spectroscopy for organic compounds of interest. A typical list of organic compounds used for CMB profiles is given below:

Species Name	Method
Fluorene**	GC/MS
Carbazole	GC/MS
Phenanthrene**	GC/MS
Anthracene**	GC/MS
Acridine	GC/MS
Dibenzothiophene	GC/MS
Fluoranthene**	GC/MS
Pyrene**	GC/MS
Benzo(c)phenanthrene**	GC/MS
Chrysene**	GC/MS
Retene	GC/MS
Benzo(b)napthol(1,2 d)	GC/MS
Benzo(b+k)fluoranthene**	GC/MS
Benzo(e)pyrene**	GC/MS
Benzo(a)pyrene**	GC/MS
Perylene**	GC/MS
Indno(1,2,3-c,d)pyrene**	GC/MS
Benzo(ghi)perylene**	GC/MS
dibenz(a,h)anthracene**	GC/MS
tetracosane	GC/MS
pentacosane	GC/MS
hexacosane	GC/MS
heptacosane	GC/MS
octacosane	GC/MS
Nonacosae	GC/MS
Triacosane	GC/MS

** = PAHs

Aside from the chemical characterization, the particulate emission rate also will be obtained from flow parameters and mass determinations (2 sizes fractions). The cost is provided in detail in the following table. Possible savings may result from the provision of woodstoves from manufactures.

Cost Estimate for Source Characterization

Labour

Tasks	CSD	MEY	MU	EL	Word Processing
1. Setup	20	10	50	50	-
2. Sampling	20	10	25	25	-
3. Data Analysis	10	25		25	-
4. Report	10	20	-	-	30
5. Project Management	-	30	-	-	-
	60	105	75	100	30
Total (Labour)	6,900	7,875	3,000	6,500	1,350
Labour	25,625				
Non Labour	56,200				
TOTAL	$81,825				

Source Characterization Costs - Non Labour

Sampling Train Construction	$35,000
Stoves (3 types)	$4,500
Wood (3 types)	500
Other consumables (filters, gases, etc.)	5,200
Computer costs	2,000
Analysis (IC, TOR, XRF, GC/MS) @ 900 combined per sample)	9,000

Assuming Rental/borrowing of sampling train $51,825 (-35,000)

Additionally:

Assuming manufacturer supplied stove units $47,325 (-4,500)

SUMMARY

The program outlined will provide answers to the first two questions raised earlier namely

i) is there the potential for significant air quality impacts due to residential wood combustion in Ontario.

ii) If there is, what is the magnitude of the impacts?

At this stage the third question can be addressed and appropriate consideration of control measures can be undertaken.

8 REFERENCES 8-1

8 REFERENCES

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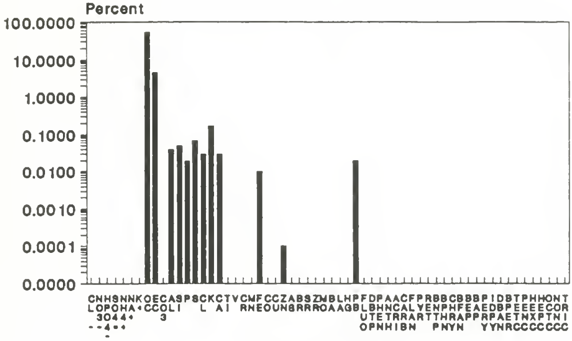
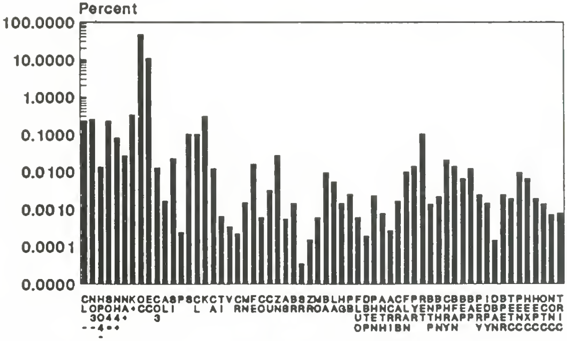
APPENDIX A

Woodstove Source Profile
PM-2.5 Fraction (JA Rau Thesis)



Pacific NW Profile Project

Woodstove Source Profile
PM-2.5 Fraction Composite



Pacific NW Profile Project

	MEDFORD, OREGON SOURCE PROFILE		PORTLAND/SEATTLE SOURCE PROFILE		POCATELLO, IDAHO SOURCE PROFILE		OVERALL AVERAGE SOURCE PROFILE		PH.O. T COLD BURNING
CHEMICAL SPECIES	AVERAGE	STD.ERR.	AVERAGE	STD.ERR.	AVERAGE	STD.ERR.	AVERAGE	STD.ERR.	AVERAGE
F -	0.00008 +-	0.43300	0.00013 +-	0.00004	0.00010 +-	0.01247	0.00010 +-	0.00004	ND
CL -	0.47850 +-	0.82055	0.08823 +-	0.05465	0.07613 +-	0.01247	0.22685 +-	0.38186	ND
NO3-	0.56840 +-	1.23892	0.09590 +-	0.01625	0.06637 +-	0.03169	0.25966 +-	0.48331	ND
HPO4-	0.01338 +-	1.73013	0.00805 +-	0.01394	0.02047 +-	0.01081	0.01337 +-	0.01333	ND
SO4=	0.40165 +-	2.26829	0.19565 +-	0.02401	0.14060 +-	0.04885	0.22785 +-	0.10281	ND
NH4+	0.05615 +-	2.81529	0.09850 +-	0.02100	0.07477 +-	0.03151	0.08178 +-	0.03047	ND
NA+	0.03610 +-	3.29136	0.04098 +-	0.03626	0.00687 +-	0.02766	0.02780 +-	0.02896	ND
MG+	0.00025 +-	0.00050	0.00378 +-	0.00654	0.00227 +-	0.00557	0.00229 +-	0.00439	ND
K+	0.83425 +-	4.06032	0.26593 +-	0.09202	0.14647 +-	0.12917	0.34255 +-	0.26456	ND
OC	49.80460 +-	21.51202	47.17198 +-	0.80743	45.35583 +-	7.70210	47.13593 +-	6.27896	54.00000
EC	16.16865 +-	6.74240	10.07933 +-	1.92784	7.89163 +-	2.56032	10.70268 +-	5.01200	4.60000
CO3	0.03068 +-	0.06135	0.00000 +-	0.00000	0.00603 +-	0.00784	0.01280 +-	0.03514	ND
AL	0.00015 +-	0.00030	0.00103 +-	0.00178	0.00463 +-	0.00249	0.00169 +-	0.00231	0.04000
SI	0.05930 +-	0.04850	0.00155 +-	0.00130	0.00250 +-	0.00157	0.02281 +-	0.04368	0.05000
P	0.00020 +-	0.00040	0.00045 +-	0.00053	0.00007 +-	0.00009	0.00025 +-	0.00042	0.02000
S	0.15855 +-	0.04530	0.08175 +-	0.00791	0.05453 +-	0.01735	0.10225 +-	0.05339	0.07000
CL	0.12888 +-	0.03270	0.08385 +-	0.02459	0.08677 +-	0.01523	0.10102 +-	0.03706	0.03000
K	0.49663 +-	0.03370	0.25215 +-	0.06993	0.11767 +-	0.11133	0.30437 +-	0.20382	0.17000
CA	0.01772 +-	0.00605	0.00975 +-	0.00435	0.00863 +-	0.00153	0.01235 +-	0.00823	0.03000
TI	0.00175 +-	0.00000	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00064 +-	0.00201	ND
V	0.00098 +-	0.00195	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00035 +-	0.00112	ND
CR	0.00063 +-	0.00125	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00023 +-	0.00072	ND
MN	0.00323 +-	0.00160	0.00053 +-	0.00025	0.00050 +-	0.00013	0.00150 +-	0.00247	ND
FE	0.04243 +-	0.06425	0.00150 +-	0.00082	0.00007 +-	0.00071	0.01599 +-	0.03737	0.01000
CO	0.00170 +-	0.00070	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00062 +-	0.00151	ND
NI	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00000 +-	0.00000	ND
CU	0.00888 +-	0.01425	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00323 +-	0.00834	ND
ZN	0.05345 +-	0.06820	0.00568 +-	0.00111	0.02130 +-	0.01019	0.02731 +-	0.04095	0.00010
GA	0.00013 +-	0.00025	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00005 +-	0.00014	ND
AS	0.00110 +-	0.00015	0.00045 +-	0.00034	0.00000 +-	0.00043	0.00056 +-	0.00098	ND
SE	0.00020 +-	0.00040	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00007 +-	0.00023	ND
BR	0.00270 +-	0.00030	0.00083 +-	0.00023	0.00060 +-	0.00030	0.00145 +-	0.00179	ND
RB	0.00050 +-	0.00020	0.00083 +-	0.00019	0.00000 +-	0.00048	0.00048 +-	0.00047	0.03000
SR	0.00010 +-	0.00000	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00004 +-	0.00011	ND
Y	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00000 +-	0.00000	ND
ZR	0.00043 +-	0.00000	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00015 +-	0.00049	ND
MO	0.00168 +-	0.00335	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00061 +-	0.00193	ND
PD	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00000 +-	0.00000	ND
AG	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00000 +-	0.00000	ND
CD	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00063 +-	0.00042	0.00017 +-	0.00034	ND
IN	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00000 +-	0.00000	ND
SN	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00000 +-	0.00000	ND
SB	0.00000 +-	0.00000	0.00110 +-	0.00067	0.00033 +-	0.00026	0.00049 +-	0.00064	ND
BA	0.02070 +-	0.00000	0.00450 +-	0.00301	0.00190 +-	0.00248	0.00968 +-	0.02331	ND
LA	0.00118 +-	0.00235	0.00567 +-	0.00354	0.01113 +-	0.00492	0.00553 +-	0.00498	ND
HG	0.00390 +-	0.00000	0.00000 +-	0.00000	0.00000 +-	0.00000	0.00142 +-	0.00448	ND
PB	0.00698 +-	0.00525	0.00010 +-	0.00017	0.00000 +-	0.00017	0.00257 +-	0.00518	0.02000
FLUORENE	0.00066 +-	0.00001	0.00064 +-	0.00079	0.00054 +-	0.00061	0.00062 +-	0.00066	NM
DIBENZOTHIOPHENE	0.00035 +-	0.00008	0.00010 +-	0.00005	0.00012 +-	0.00001	0.00020 +-	0.00023	NM
PHENANTHRENE	0.00264 +-	0.00070	0.00133 +-	0.00041	0.00306 +-	0.00265	0.00227 +-	0.00212	NM
ANTHRACENE	0.00076 +-	0.00008	0.00065 +-	0.00034	0.00100 +-	0.00123	0.00078 +-	0.00077	NM

	MEDFORD, OREGON SOURCE PROFILE		PORTLAND/SEATTLE SOURCE PROFILE		POCATELLO,IDAHO SOURCE PROFILE		OVERALL AVERAGE SOURCE PROFILE		PH.D. T COLD BURNING
CHEMICAL SPECIES	AVERAGE	STD.ERR.	AVERAGE	STD.ERR.	AVERAGE	STD.ERR.	AVERAGE	STD.ERR.	AVERAGE
ACRIDINE	0.00054 +-	0.00008	0.00013 +-	0.00002	0.00012 +-	0.00001	0.00028 +-	0.00041	NM
CARBAZOLE	0.00378 +-	0.00007	0.00059 +-	0.00050	0.00037 +-	0.00034	0.00169 +-	0.00298	NM
FLUORANTHENE	0.01242 +-	0.00583	0.00905 +-	0.00540	0.00820 +-	0.00306	0.01005 +-	0.00747	NM
PYRENE	0.02087 +-	0.00660	0.01043 +-	0.00613	0.00998 +-	0.00257	0.01410 +-	0.01377	NM
RETENE	0.12719 +-	0.00940	0.12570 +-	0.05933	0.09967 +-	0.06372	0.10552 +-	0.08801	NM
BENZO(B)NAPTHO(1,2-D)THIOPHENE	0.00249 +-	0.00043	0.00035 +-	0.00038	0.00136 +-	0.00020	0.00140 +-	0.00187	NM
BENZO(C)PHENANTHRENE	0.00542 +-	0.00237	0.00026 +-	0.00022	0.00012 +-	0.00001	0.00217 +-	0.00362	NM
CHRYSENE	0.03802 +-	0.00356	0.01200 +-	0.00479	0.01068 +-	0.00152	0.02019 +-	0.02794	NM
BENZO(B+K)FLUORANTHENE	0.02460 +-	0.00274	0.00911 +-	0.00582	0.00884 +-	0.00058	0.01420 +-	0.02234	NM
BENZO(E)PYRENE	0.01229 +-	0.00186	0.00345 +-	0.00067	0.00341 +-	0.00068	0.00650 +-	0.00927	NM
BENZO(A)PYRENE	0.02306 +-	0.00313	0.00564 +-	0.00482	0.00654 +-	0.00133	0.01241 +-	0.01685	NM
PERYLENE	0.00197 +-	0.00030	0.00091 +-	0.00025	0.00313 +-	0.00321	0.00240 +-	0.00250	NM
INDENO(1,2,3-C,D)PYRENE	0.02034 +-	0.00010	0.00047 +-	0.00034	0.00267 +-	0.00078	0.00146 +-	0.04453	NM
DIBENZ(A,H)ANTHRACENE	0.00061 +-	0.00010	0.00017 +-	0.00004	0.00017 +-	0.00008	0.00015 +-	0.00007	NM
BENZO(GHI)PERYLENE	0.01459 +-	0.00010	0.00179 +-	0.00112	0.00349 +-	0.00065	0.00248 +-	0.00141	NM
TETRACOSANE	0.00096 +-	0.00077	0.00100 +-	0.00128	0.00073 +-	0.00079	0.00189 +-	0.00304	NM
PENTACOSANE	0.01817 +-	0.00421	0.00058 +-	0.00077	0.00847 +-	0.00902	0.00960 +-	0.01741	NM
HEXACOSANE	0.01555 +-	0.00145	0.00013 +-	0.00002	0.00205 +-	0.00248	0.00652 +-	0.01443	NM
HEPTACOSANE	0.00385 +-	0.00249	0.00019 +-	0.00010	0.00051 +-	0.00053	0.00196 +-	0.00226	NM
OCTACOSANE	0.00334 +-	0.00491	0.00011 +-	0.00003	0.00012 +-	0.00001	0.00135 +-	0.00282	NM
NONACOSANE	0.00111 +-	0.00008	0.00069 +-	0.00099	0.00023 +-	0.00014	0.00072 +-	0.00089	NM
TRIACONTANE	0.00121 +-	0.00008	0.00081 +-	0.00049	0.00012 +-	0.00001	0.00077 +-	0.00084	NM

ND = NOT DETECTED; NM = NOT MEASURED

APPENDIX B

Figure 1: Dilution Sampling Train Schematic

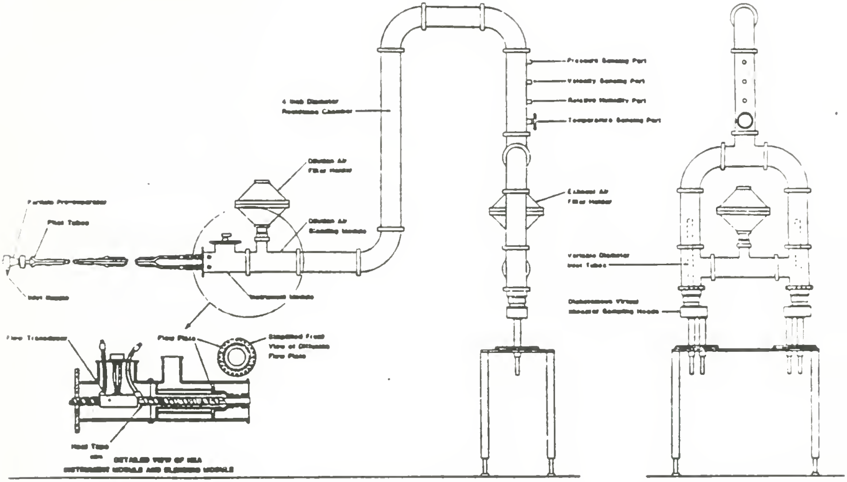

Pressure Sensing Port
Velocity Sensing Port
Relative Humidity Port
Temperature Sensing Port
4 Inch Diameter Residence Chamber
Dilution Air Filter Holder
Exhaust Air Filter Holder
Dilution Air Sampling Module
Particle Preseparator
Variable Diameter Inlet Tubes
Instrument Module
Inlet Nozzle
Dichotomous Virtual Impactor Sampling Heads
Flow Transducer
Flow Plate
Simplified Front View of Diffusion Flow Plate
Heat Tape

Figure 2: Woodstove Dilution Sampling Tunnel